

# AGN Feedback in Galaxy Groups: the Delicate Touch of Self-Regulated Outflows

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## ABSTRACT

AGN heating, through massive subrelativistic outflows, might be the key to solve the long-lasting ‘cooling flow problem’ in cosmological systems. In a previous paper, we showed that cold accretion feedback and, to a lesser degree, Bondi self-regulated models are in fact able to quench cooling rates for several Gyr, at the same time preserving the main cool core features, like observed density and temperature profiles. Is it true also for lighter systems, such as galaxy groups? The answer is globally yes, although with remarkable differences. Adopting a modified version of the AMR code FLASH 3.2, we found that successful 3D simulations with cold and Bondi models are almost convergent in the galaxy group environment, with mechanical efficiencies in the range  $5 \times 10^{-4} - 10^{-3}$  and  $5 \times 10^{-2} - 10^{-1}$ , respectively. The evolutionary storyline of galaxy groups is dominated by a quasi-continuous gentle injection with sub-Eddington outflows (with mechanical power  $P \sim 10^{44}$  erg s<sup>-1</sup>,  $v \sim 10^4$  km s<sup>-1</sup>). The cold and hybrid accretion models present, in addition, very short quiescence periods, followed by moderate outbursts (10 times the previous phase), which generate a series of 10–20 kpc size cavities with high density contrast, temperatures similar to the ambient medium and cold rims. After shock heating, a phase of turbulence promotes gas mixing and diffusion of metals, which peak along jet-axis (up to 40 kpc) during active phases. At this stage the tunnel, produced by the enduring outflow (hard to detect in the mock X-ray surface brightness maps), is easily fragmented, producing tiny buoyant bubbles, typically a few kpc in size. In contrast to galaxy clusters, the AGN self-regulated feedback has to be persistent, with a ‘delicate touch’, rather than rare and explosive strokes. This evolutionary difference dictates that galaxy groups are not scaled-down versions of clusters: AGN heating might operate in different regimes, contributing to the self-similarity breaking observed.

**Key words:** cooling flows – galaxies: active – galaxies: jets – hydrodynamics – intergalactic medium – X-rays: galaxies: groups.

## 1 INTRODUCTION

Remarkably, most of the galaxies in the universe reside in small groups (up to 70% in the nearby zone; Geller & Hucra 1983; Mulchaey 2000). Nevertheless, relatively little attention has been devoted to groups with respect to their ‘big brothers’, galaxy clusters. Groups, with typical masses around  $10^{13} M_{\odot}$ , are thus a key class of objects, containing a significant fraction of the overall universal baryon budget and being a nursery for massive (early-type) galaxies.

Galaxy groups are X-ray sources, with diffuse extended (50–500 kpc) emission similar to that of rich clusters, but with lower luminosities, ranging from  $10^{41}$  erg s<sup>-1</sup> up to

several times  $10^{43}$  erg s<sup>-1</sup>, with temperatures around  $\sim 0.3 - 2$  keV (Mulchaey 2000).

It is known that clusters and groups do not follow the global scaling relations predicted by self-similar models (e.g. Kaiser 1986; Evrard & Henry 1991; Osmond & Ponman 2004; Vikhlinin et al. 2006). Groups are not perfect scaled down versions of clusters. If groups are sampled at sufficiently large radii, some X-ray scaling relations (e.g. luminosity–temperature, mass–temperature) seem similar to those followed by massive clusters (Osmond & Ponman 2004; Sun et al. 2009), with the scatter increasing for  $T \lesssim 1$  keV. However, systematic differences between groups and clusters exist, with the former having clearly lower gas (and baryon) fractions and flatter entropy profiles (Finoguenov et al. 2005; Voit 2005; Sun et al. 2009). Moreover, groups have

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velocity dispersions of several hundreds  $\text{km s}^{-1}$ , comparable to the internal velocity dispersion of individual galaxies. For this reason, some processes are more (merging) or less (ram-pressure stripping, galaxy harassment) relevant than in clusters.

The discrepancies between the observed scaling relations and the predictions of self-similar models, and especially the systematic differences between groups and clusters quoted above, can be explained by the presence of non-gravitational heating, acting during or after the gravitational collapse. In lower mass systems the same amount of energy per unit mass has a stronger effect. This is a key point for the mechanical AGN feedback problem investigated here and in our previous work (Gaspari et al. 2011, G11 thereafter).

As in clusters and elliptical galaxies, many galaxy groups display the typical signatures of cooling flows<sup>1</sup> (a most notable example being NGC 5044). In the center, where the radiative cooling time is the shortest ( $\sim 10^7$  yr), the temperature of the intragroup medium (IGM) drops by nearly 50%. Moreover, the X-ray surface brightness is sharply peaked, with the maximum coincident with a massive elliptical galaxy.

A large sample of X-ray groups is presented in Sun et al. (2009). Gathering 43 objects with *Chandra* data, they confirmed the existence of a ‘universal’ temperature profile (De Grandi & Molendi 2002; Voit 2005; Leccardi & Molendi 2008). The group profiles are slightly steeper than those of clusters for  $r \geq 0.15 r_{500}$ . In the inner cool core, the scatter is significant: the majority presents positive gradients, while few are approaching a flat temperature profile (a possible signature of a heating cycle). Sun et al. produced also the entropy profiles, which retain the thermal history of the gas. They again confirmed previous important works (Ponman et al. 1999, 2003; Finoguenov et al. 2002), suggesting deviations in the entropy from the self-similar relation ( $K \propto T$ ), showing a clear flat core, and an excess relative to massive clusters.

One of the most striking riddles of galaxy group astrophysics concerns the so called ‘cooling flow problem’. This paper attempts to solve it, finding plausible consistent models, as has been done for galaxy clusters in G11. The classical cooling flow (CF) model (Fabian 1994 for a review) predicts that, as the gas radiates, its entropy decreases, and thus gets compressed by the surrounding gas, causing it to subsonically flow inward. The estimated (isobaric) cooling rates is given by:

$$\dot{M} \simeq \frac{2}{5} \frac{\mu m_p}{k_B T} L_X, \quad (1)$$

where  $L_X$  is the X-ray luminosity,  $\mu$  the mean molecular weight,  $k_B$  the Boltzmann constant,  $m_p$  the proton mass. For typical luminosities of groups ( $\approx 10^{43} \text{ erg s}^{-1}$ ), the relation implies cooling rates of several tens  $M_\odot/\text{yr}$ . Such high predicted  $\dot{M}$  have been in contrast for years with the estimates of star formation rates and cold gas masses (at least an order of magnitude lower), but the definitive observational evidence against the traditional CF model has been the spectral analysis of XMM-RGS spectra (e.g. Peterson et

al. 2001, 2003; Tamura et al. 2003; Peterson & Fabian 2006).

In the last decade the new generation *XMM-Newton* and *Chandra* telescopes have radically changed the panorama of the evolution of hot gas in groups and clusters. *ROSAT-HRI* and, especially, *Chandra* high resolution X-ray images show clear evidence of AGN-gas interaction from giant elliptical galaxies (gE) to clusters (Böhringer et al. 1993; Blanton et al. 2001; Finoguenov & Jones 2001; Jones et al. 2002; McNamara & Nulsen 2007 and references therein). Evidences of such activity have also been identified in many groups (Allen et al. 2006; Morita et al. 2006; Jetha et al. 2008; Gastaldello et al. 2009). The fairly common presence of X-ray cavities, often coincident with lobes of radio emission connected to the core of the central galaxy by a radio jet, indicates that AGN inject energy in the IGM in kinetic form (outflows) and as relativistic particles.

Moreover, from dozens of giant ellipticals (gE) (Nulsen et al. 2007) to rich clusters (Rafferty et al. 2006, 2008) there is a continuous scaling relation between the AGN power, associated with the cavity formation, and the core X-ray luminosity. This trend is more evident in low mass systems. Although this connection is likely to be a necessary but not a sufficient requirement for a successful heating scenario, it strongly suggests that the dominant heating process manifests itself generating bubbles in the ICM, through some kind of ‘directional’ energy input, such as jets or collimated outflows (rather than spherically symmetric forms).

AGN outflows seem to be a very promising mechanism to simultaneously explain the quenching of cooling flows (and star formation), the deviation of scaling relations from self-similar laws and the presence of X-ray cavities and weak shocks in the intergalactic (interstellar) medium. As anticipated before, the impact of this type of heating is much more evident in less bounded systems, such as groups. We can therefore speculate that gentler outflows are more appropriate to regulate the thermodynamic evolution of the IGM, while strong bursts should easily deform the main properties.

Regarding clusters, we can account for several variegated computations (e.g. Ruszkowski et al. 2004; Omma et al. 2004; Brüggén et al. 2005; Brighenti & Mathews 2006; Sternberg et al. 2007; Gaspari et al. 2009, 2011 among others), but little work has been done to explore the role of AGN heating on the intragroup medium, especially from a theoretical and numerical point of view. Brighenti & Mathews (2003) studied thermal heating (plus conduction) in 2D simulations, showing that this type of feedback, while very efficient in stopping the cooling process, often generates negative temperature gradients, with the total erasure of galactic cooling flows commonly observed in gE (Sun et al. 2005, 2007). Carrying out cosmological simulations (Puchwein et al. 2008; McCarthy et al. 2010) does not permit, nowadays, a detailed analysis of the feedback dynamics in the inner cool core, mainly because of the lack of resolution, and are thus more suited to study global sample-averaged properties. Further, none of the above mentioned works has investigated a purely mechanical feedback.

In this paper we will therefore describe, for the first time, 3D self-regulated hydrodynamical simulations of AGN outflows in an exemplary galaxy group, lasting at least 7

<sup>1</sup> Interestingly, the analogues of non-cool core clusters on the group scale have been rarely detected (Johnson et al. 2011).

Gyr. The positive results of similar simulations for rich galaxy clusters (G11) are a strong motivation for a detailed analysis of this (mechanical) feedback mechanism in lower mass systems.

As in G11, we assume that AGN outflows are the key element in solving the cooling flow problem. The physical foundation is that the relativistic jet, produced by the active nucleus, entrains ambient gas, strongly decelerating within a scale-length of just a few kpc. Such subrelativistic AGN outflows have been observed in several cD galaxies in every band, thanks to blueshifted absorption lines: optical (Nesvadba et al. 2008, 2011), UV and X-Ray (see Crenshaw et al. 2003 for a review), 21-cm (Morganti et al. 2005, 2007; see also the references in G11). They occur at a distance of a kpc with velocities around  $10^3 - 10^4 \text{ km s}^{-1}$ . The geometry of the bipolar outflows is still unclear, with usually narrow opening angles, and possibly some kind of precession.

The timing of the feedback is also an important issue. From observations and from a ‘thermostat’ assumption the duty cycle has to be similar to the cooling time, around  $10^7$  yr. We will simplify the feedback self-regulation, testing hot (Bondi) or cold accretion models with different mechanical efficiencies. Fully 3D simulations are required to compute the chaotic and turbulent flow, with associated instabilities.

In summary, this work will focus on a set of heated cooling flow models with a variety of AGN feedback mechanisms, aimed to answer the following key question: *are AGN outflows able to prevent the IGM from cooling and at the same time preserve the observed cool core appearance for many Gyr?*

## 2 THE COMPUTATIONAL PROCEDURE

In order to study the behaviour of AGN outflows in galaxy groups, we carried out several simulations with a substantially modified version of FLASH 3.2 (Fryxell et al. 2000), a popular 3D adaptive mesh refinement (AMR) code. FLASH uses the Message-Passing Interface (MPI) library to achieve portability and efficient scalability on a variety of different parallel high-performance computing systems. The simulations were usually run on 128 processors of IBM P575 Power 6 (SP6) at CINECA supercomputing centre.

We tested different numerical schemes to solve the hydrodynamic Euler equations. As in G11, we widely used the Piecewise-Parabolic Method (PPM) solver (Colella & Woodward 1984), particularly appropriate to describe shock fronts. It uses directional splitting to advect quantities (Strang 1968). This makes the instantaneous injection of the outflow not trivial, since we must manage two equal timesteps with a sweep  $x-y-z$  and then  $z-y-x$ . Thus, we decided to also adopt other unsplit methods (single timestep evolution). We tested Roe and Lax-Friedrichs, with different slope limiters (van Leer, minmod, etc.). They work pretty well for smooth flows, but not for a powerful jet ignition, producing unstable results also with low Courant-Friedrichs-Lewy (CFL) numbers ( $< 0.1$ ). On the contrary, the HLLC solver (Toro 1999) is very stable also for higher CFL numbers ( $\sim 0.5$ ), with a good description of shocks and contact discontinuities. In the end, results with both methods are comparable, with PPM being more accurate (3rd order),

while HLLC faster and more manageable. In many cases we preferred accuracy over speed.

The innovations implemented in FLASH reside, mainly, in several source and sink terms added to the usual hydro-equations. In conservative form:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = \alpha \rho_* - q \frac{\rho}{t_{\text{cool}}} + S_{1,\text{jet}}, \quad (2)$$

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v} \otimes \mathbf{v}) + \nabla P = \rho \mathbf{g}_{\text{DM}} + S_{2,\text{jet}}, \quad (3)$$

$$\begin{aligned} \frac{\partial \rho \varepsilon}{\partial t} + \nabla \cdot [(\rho \varepsilon + P) \mathbf{v}] = \rho \mathbf{v} \cdot \mathbf{g}_{\text{DM}} + \alpha \rho_* \left( \varepsilon_0 + \frac{\mathbf{v}^2}{2} \right) \\ - n_e n_i \Lambda(T, Z) + S_{3,\text{jet}}, \end{aligned} \quad (4)$$

$$P = (\gamma - 1) \rho \left( \varepsilon - \frac{\mathbf{v}^2}{2} \right) \quad (5)$$

where  $\rho$  is the gas density,  $\mathbf{v}$  the velocity,  $\varepsilon$  the specific total energy (internal and kinetic),  $P$  the pressure,  $\mathbf{g}_{\text{DM}}$  the gravitational acceleration (due to the dark matter halo plus the central elliptical, see below), and  $\gamma = 5/3$  the adiabatic index. The temperature is computed from  $P$  and  $\rho$  using (5), with an atomic weight  $\mu \simeq 0.62$ , appropriate for a totally ionized plasma with 25% He in mass.

In G11 we describe in-depth all the source and sink terms (right hand side of the first three equations). Here we give a summary.

Radiative cooling is modeled according to Sutherland & Dopita (1993) cooling function  $\Lambda(T, Z)$  for a fully ionized plasma ( $n_e$  and  $n_i$  are the number density of electrons and ions). For typical groups, the central metallicity  $Z$  is about solar (e.g., Rasmussen & Ponman 2009), with a negative gradient at larger radii. For simplicity, we set the abundance equal to  $1 Z_{\odot}$ .

Supernovae Ia (SNIa) and stellar winds (SW), in the central elliptical galaxy are implemented following Brighenti & Mathews (2002), with a stellar mass loss rate  $\alpha(t)$  dominated by stellar winds  $\propto t^{-1.3}$ .

The key prescription for treating the cold gas is the dropout term (Eq. (2)), proportional to  $q = 2 \exp(-(T/5 \times 10^5)^2)$ . It removes the gas below  $T = 10^{4-5} \text{ K}$ , whose physical evolution cannot be properly followed by our code<sup>2</sup>. Because it has been proved that the total mass of cooled gas is insensitive to the presence of the dropout term or its functional form (see Brighenti & Mathews 2000), we can still calculate the gas cooling rate accurately.

Outflow source terms  $S_{1,2,3,\text{jet}}$  will be explained for every type of feedback in Section 2.2. Injection will be done with two different methods: directly into the domain (without a mass inflow) or through boundary condition at  $z = 0$  ( $S_1 > 0$ ).

We calculate the flow evolution for 7 Gyr. Local cosmological systems have very different formation times and are subject to relatively frequent mergers (Cohn & White 2005). We conservatively decided to run our simulations for such a long time to take into account the systems which do not undergo major mergers since  $z \sim 0.7$ . Moreover, cool cores in massive objects may survive major mergers (e.g.,

<sup>2</sup> Tests without the dropout show the artificial assembly of cold clumps near the center.

**Table 1.** Parameters and properties of the most relevant models.

Model	Feedback	efficiency ( $\epsilon$ )	Notes
CF	no AGN heating	-	-
Bc1em2	Bondi	$10^{-2}$	continuous
Bc5em2	Bondi	$5 \times 10^{-2}$	continuous
Bc1em1	Bondi	$10^{-1}$	continuous
Bi1em3	Bondi	$10^{-3}$	cold timing
Bi1em2	Bondi	$10^{-2}$	cold timing
Bi5em2	Bondi	$5 \times 10^{-2}$	cold timing
Bi1em1	Bondi	$10^{-1}$	cold timing
C5em5	cold	$5 \times 10^{-5}$	-
C1em4	cold	$10^{-4}$	-
C5em4	cold	$5 \times 10^{-4}$	-
C1em3	cold	$10^{-3}$	-
Int510l	5 - 10 Myr cycle	-	$P_j = 10^{-5} P_{\text{Edd}}$
Int510m	5 - 10 Myr cycle	-	$P_j = 10^{-4} P_{\text{Edd}}$
Int510h	5 - 10 Myr cycle	-	$P_j = 10^{-3} P_{\text{Edd}}$
Eth50	thermal (+ Bc)	$5 \times 10^{-3}$	50% $E_{\text{th}}$
IO1-9	InOut (+ Bc)	$10^{-3}$	$\dot{M}_{\text{in}} = 0.1 \dot{M}_{\text{acc}}$
IOen40	InOut (+ Bc)	$5 \times 10^{-3}$	$40 \dot{M}_{\text{out}}$ (IO3-7)
IOen80	InOut (+ Bc)	$5 \times 10^{-3}$	$80 \dot{M}_{\text{out}}$ (IO3-7)

Burns et al. 2008), implying that the central AGN feedback is continuously needed.

Note that several feedback schemes could delay excessive gas cooling for only 1 Gyr before failing (see G11). Thus, we stress that a few hundreds Myr evolution is not sufficient to make predictions on the heating versus cooling regulation and might lead to misleading extrapolations.

## 2.1 The group model and initial conditions

We choose NGC 5044 as the template for a typical X-ray bright group of galaxies: all the results we present should be relevant for any object in this category. NGC 5044 was one of the first cool core groups observed, due to its high X-ray brightness, with low redshift 0.009 (see Buote et al. 2003; Gastaldello et al. 2009; David et al. 2009, for recent Chandra and XMM data). The estimated X-ray bolometric (0.1 – 100 keV) luminosity is around  $2 \times 10^{43} \text{ erg s}^{-1}$ , with a virial mass of  $\sim 4 \times 10^{13} M_{\odot}$ . The large scale morphology is very smooth and nearly spherical, despite a little disturbance in the form of a south-eastern cold front. At the contrary, the core ( $\sim 10$  kpc) has been strongly perturbed by recent outbursts from the central AGN. The group presents many small radio quiet cavities with a nearly isotropic distribution and moderate mechanical power ( $\sim 10^{42} \text{ erg s}^{-1}$ ). The two biggest cavities at larger radii (10 – 20 kpc) are instead filled with radio emission at 235 MHz (David et al. 2009) and the associated mechanical power seems to be able to balance radiative losses. The NGC 5044 X-ray image also shows several cold filaments coincident with H $\alpha$  and dust emission, indicating a physical connection between the various gas phases (Gastaldello et al. 2009). The GMRT observation (610 MHz) reveals the presence of extended radio emission with a torus-like morphology, threaded by the largest filament (probably cold material being uplifted from the center).

The cooling time of the hot gas within the central 2 kpc is just  $\sim 4 \times 10^7$  yr. In the absence of feedback, a pure cooling flow model predicts tens of  $M_{\odot}/\text{yr}$  (see Eq. (1)),

while observations suggest the cooling rate is at least an order of magnitude lower, less than a few  $M_{\odot}/\text{yr}$  (David et al. 2009). This is the key requirement for our computed models.

This galaxy group consists of a luminous giant elliptical galaxy (NGC 5044) surrounded by a cluster of  $\sim 150$  low luminosity dwarf galaxies, mostly of early type. Thus, we choose to model the elliptical galaxy with a de Vaucouleurs profile (Mellier & Mathez 1987) with total stellar mass  $M_{\star} \sim 3.4 \times 10^{11} M_{\odot}$  and effective radius  $r_e \sim 10$  kpc (Buote et al. 2004).

We start our calculations with the hot gas in spherical hydrostatic equilibrium in the potential well generated by the total system mass. We use the observed  $T(r)$  and  $n(r)$  (Buote et al. 2003, 2004, see the dotted lines of Fig. 1) to calculate the total gravitational potential under the assumption of hydrostatic equilibrium. At the virial radius the gas fraction is  $\sim 0.11$ , a reasonable value for X-ray bright groups (Mathews et al. 2005).

The computational rectangular 3D box in all of our models extends slightly beyond the group virial radius,  $R_{104}$ . We simulate the  $z \geq 0$  half-space with symmetric boundary condition at  $z = 0$ , while elsewhere we set prolonged initial conditions with only outflow allowed. Despite the AMR capability of FLASH, we decided to use a number of concentric fixed grids in cartesian coordinates. This ensures a proper resolution of the waves and cavities generated in the cluster core by the AGN outflows. We use a set of 10 grid levels (basic blocks of  $8 \times 8 \times 4$  points), with the zone linear size doubling among adjacent levels. The finest, inner grid has a resolution of 488 pc and covers a spherical region of  $\sim 20$  kpc in radius. In general, grids of every level extend radially for about 40 cells. This simple method is the best way found to cover large spatial scales (hundreds pc up to Mpc) and at the same time integrating the system for several Gyr, using moderate computing resources.

## 2.2 Outflow generation

We adopt a purely mechanical AGN feedback in form of nonrelativistic, collimated outflows. The implementation is similar to the galaxy cluster outflows of G11.

In considering massive slow outflows, we are implicitly assuming that the relativistic jet entrains some ICM mass ( $\dot{M}_{\text{act}}$ ), or in a similar way, that radio jets are highly relativistic on pc scale, but rapidly decrease to subrelativistic velocities within few kpc from the black hole (Giovannini 2004).

As in G11 we show results only for models with cylindrical jets, with velocity parallel to the  $z$ -axis. We have calculated few simulations with conical (or precessing) outflows and verified they have a similar impact on the global properties of the flow. In fact, the pressure of the surrounding gas collimates the outflows within few tens kpc.

In this paper we will focus mainly on the two most successful models adopted for clusters in G11: cold and Bondi feedback.

In the cold feedback<sup>3</sup> an outflow is activated only when

<sup>3</sup> See also Soker 2006 for a similar type of heating.

gas cools to very low temperature within a spherical region  $r < 3$  kpc, and drops out from the flow. If  $\Delta M_{\text{cool}}$  is the mass cooled in the aforementioned region during a single timestep, the injected kinetic energy (in the following timestep) is given by:

$$\Delta E_{\text{jet}} = \epsilon \Delta M_{\text{cool}} c^2. \quad (6)$$

This energy is given to the hot gas located in a small region at the centre of the grid (the ‘active jet region’), whose size is always<sup>4</sup>  $2 \times 4$  cells ( $\sim 1$  kpc wide, 2 kpc high), containing a hot gas mass  $M_{\text{act}}$ :

$$\frac{1}{2} M_{\text{act}} v_{\text{jet}}^2 = \Delta E_{\text{jet}}. \quad (7)$$

We will see that the frequency and strength of the feedback events strongly depend on the mechanical efficiency  $\epsilon$ , which has typical values  $10^{-4} - 10^{-3}$  (see Table 1), almost an order lower than galaxy clusters.

In the Bondi feedback the outflows are triggered by the usual prescription:

$$\dot{M}_{\text{B}} = 4\pi (GM_{\text{BH}})^2 \rho_0 / c_{s0}^3, \quad (8)$$

where  $\rho_0$  is the volume-weighted hot gas density calculated within  $\sim 2.5$  kpc, while  $c_{s0}$  is the mass-weighted sound speed in the same region. The assumed SMBH has a mass of  $3 \times 10^9 M_{\odot}$ . The outflow energy is then calculated with eq. (7), using  $\dot{M}_{\text{B}}$  instead of  $\Delta M_{\text{cool}}$ . Needless to say, the Bondi radius,  $r_{\text{B}} \sim 80$  pc, is smaller than our resolution limit, so we refrain to attach a strict physical meaning to  $\dot{M}_{\text{B}}$ . In this sense the high mechanical efficiencies adopted for Bondi models are due to the fact that the accretion should be considerably larger (because of higher inner  $\rho_0$  and lower  $c_{s0}$ ).

Besides the two main feedback schemes, we experimented some variations in the AGN generation, such as fixed intermittency, thermal feedback, direct linking between outflowing and accreting mass. These special models are often not successful and they will be briefly explained through Sections 3.4 - 3.6 (see also Table 1 for a summary).

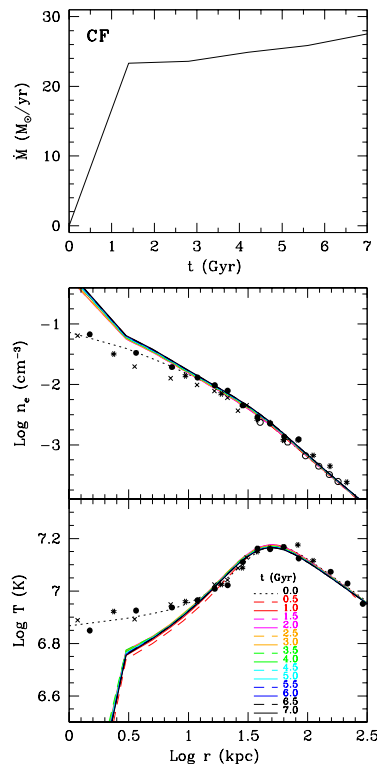
For most of the presented methods we applied injection directly in the domain with  $M_{\text{act}}$ , as stated above. In other simulations we tested also the injection of mass, momentum and energy flux through a ‘nozzle’ in the grid boundary at  $z = 0$ . This way, the jet power is expressed as:

$$\frac{1}{2} (\rho_{\text{jet}} v_{\text{jet}} A_{\text{n}}) v_{\text{jet}}^2 = \epsilon \dot{M} c^2, \quad (9)$$

with a nozzle area  $A_{\text{n}}$  of  $2 \times 2$  cells and  $\rho_{\text{jet}} \sim 0.1$  the initial central gas density. We fix the temperature of the jet to very low values, compared to the IGM, in order to keep injected thermal energy on negligible levels compared to the kinetic flux.

As noted also in G11, the results do not greatly depend on the method of injection. However, the physical approach is a bit different: in the  $M_{\text{act}}$  method we are directly modelling the entrainment, while in the nozzle injection we are specifying the properties of the ‘subgrid jet’.

<sup>4</sup> A slightly smaller or bigger jet does not alter the global evolution, see G11.



**Figure 1.** Evolution of CF model (no AGN feedback). Top panel: gas cooling rate versus time. Middle and bottom panels: temporal evolution of the gas (electron) number density and mass weighted temperature profiles, respectively. The profiles are displayed at 15 different times, as indicated in the lowermost panel. *Chandra* and *XMM-Newton* observational data of NGC 5044 are represented by star and cross points (Buote et al. 2004), filled circles (Buote et al. 2003); open circles indicate *ROSAT* data (David et al. 1994).

### 3 RESULTS

In this Section we report the results of the various simulations, exploring different types of feedback and parameters. We have analysed in detail the long term behaviour of models similar to the most successful ones in G11. Some of the properties of unsuccessful - but pedagogical - models are covered in G11.

We stress again that the main objective of the present work is investigating the global properties of the flow, such as cooling rates and azimuthally averaged profiles (density, temperature, etc.). Cavities, shocks and iron abundances will be studied in-depth elsewhere through a dedicated set of simulations at higher resolution.

#### 3.1 Pure cooling flow

As a fiducial model, we ran a simulation without AGN feedback, i.e. a pure cooling flow (CF). The results are shown in Fig. 1.

The flaws of the classical cooling flow model are clearly depicted in this evolution. Both the density and (mass weighted) temperature profiles steepen considerably in the central region: the radiative losses induce a subsonic inflow of the gas, increasing the emissivity in a vicious cycle. This trend is relatively more evident and fast in the galaxy group,

rather than in the cluster. After just 1 Gyr the cooling rate has already approached a quasi steady state, with an asymptotic value  $\sim 25 M_{\odot}/\text{yr}$ . This is the clearest discrepancy with observational data and one of the main failure of the standard cooling flow scenario.

The other two main observables,  $T(r)$  and  $n_e(r)$ , are also clearly wrong in the inner  $\sim 15$  kpc (see Sec. 1 and 2.1 for the observational references). Very cold gas, down to  $10^5$  K (which is soon dropped in our simulation), concentrate in the nucleus and generate non consistent gradients. Our feedback models have to reduce this steepening, but preserving the cool core appearance at the same time. As said in Sec. 1, galaxy groups present a more variable inner temperature profile respect to clusters. Nevertheless, the heating must not destroy the inner structure (see also Brighenti & Mathews 2002, 2003), a quite demanding requirement.

A typical signature of such a strong cooling flow is also the temporal increase of the bolometric X-ray luminosity: from  $\sim 1.9 \times 10^{43} \text{ erg s}^{-1}$  up to  $\sim 2.6 \times 10^{43} \text{ erg s}^{-1}$  at 7 Gyr.

It is interesting to investigate the global energetic budget, because the common (misleading) sense would probably associate the irradiated energy with, mainly, the drop in internal energy. However, the internal energy within  $r_{\text{vir}}$  decreases by  $\sim 7 \times 10^{58} \text{ erg}$  (that is, by less of 1%), while the potential energy drops by  $\sim 6 \times 10^{60} \text{ erg}$ , considering both the hot gas remaining in the grid and the cooled gas at the centre of the cluster. The kinetic energy stays always around  $\sim 10^{57} \text{ erg}$  and is therefore negligible. The conclusion is that energy is radiated away ( $E_{\text{rad}} \sim 6 \times 10^{60} \text{ erg}$  in 7 Gyr) mainly at the expense of the potential energy of the IGM. This behaviour was less evident in the cluster, but still present.

In order to test the effect of numerical resolution on the CF results, we calculated a CF simulation with a resolution three times higher: the results are almost identical to the lower resolution run described above. Therefore, with the adopted resolution our models are clearly in the convergence limit.

After placing the frame of the requirements for a successful feedback model, in the following we will describe the simulations with heating linked to AGN outflows. In the next Section, we will begin with the two best Bondi models and then we will discuss, from higher to lower efficiencies, computations with worse results, alternating continuous and intermittent type of feedback.

## 3.2 Bondi feedback (or entropy-regulated)

### 3.2.1 Model Bc5em2, $\epsilon_B = 5 \times 10^{-2}$

We begin to analyse the results of the simulations with AGN feedback turned on.

The Bondi accretion theory (Bondi 1952), although highly idealized with respect to the complexity expected in real accretion systems, has been widely used to estimate accretion rates on supermassive black holes, adopting Eq. (8).

Despite our resolution is far from capturing the effective Bondi radius (tens of pc) and despite the fact that the radiative cooling is important in the central region, we think that Bondi accretion is still a useful, simple feedback pre-

scription. In fact, the accretion rate is simply proportional to  $K^{-3/2}$ , where  $K = T/\rho^{2/3}$  is the entropy parameter. Thus, Bondi regulation is intrinsically a good ‘thermostat’: when the gas is cold and dense, the feedback is stronger, and vice versa.

The first good model that we obtained is Bondi accretion with efficiency  $\epsilon = 5 \times 10^{-2}$  (Fig. 2, second column), using the ‘entrainment’ injection in the active region. The zone for the weighted quantities is  $\sim 2.5$  kpc. The overall feedback is gentle and moderate, exactly as speculated.

The mean cooling rate is well below 10% of the pure cooling flow, with only a transient peak ( $\sim 3.5 M_{\odot} \text{ yr}^{-1}$ ) at 1.5 Gyr. An important feature for a successful continuous feedback, as seen in G11, is stability in time. The moderate power stays around  $10^{44} \text{ erg s}^{-1}$ , without strong variations, which allows to balance the instantaneous cooling rate in an efficient way.

The mass-weighted temperature profiles are in agreement with observations in the nucleus of the group, with a smooth and almost flat curve. In the outer regions tiny acoustic oscillations are present, while between 10-30 kpc the continuous injection of energy tends to slightly overheat this region, especially at late times. The density profiles also show little variation from the initial observed ones, an indication that the gas is not accumulating and peaking in the core.

Another relevant consideration is that the Bondi rate is always sub-Eddington (between  $10^{-3} - 10^{-2}$  Eddington rate). Observations of X-ray bright elliptical galaxies (e.g. Allen et al. 2006) also point towards similar values.

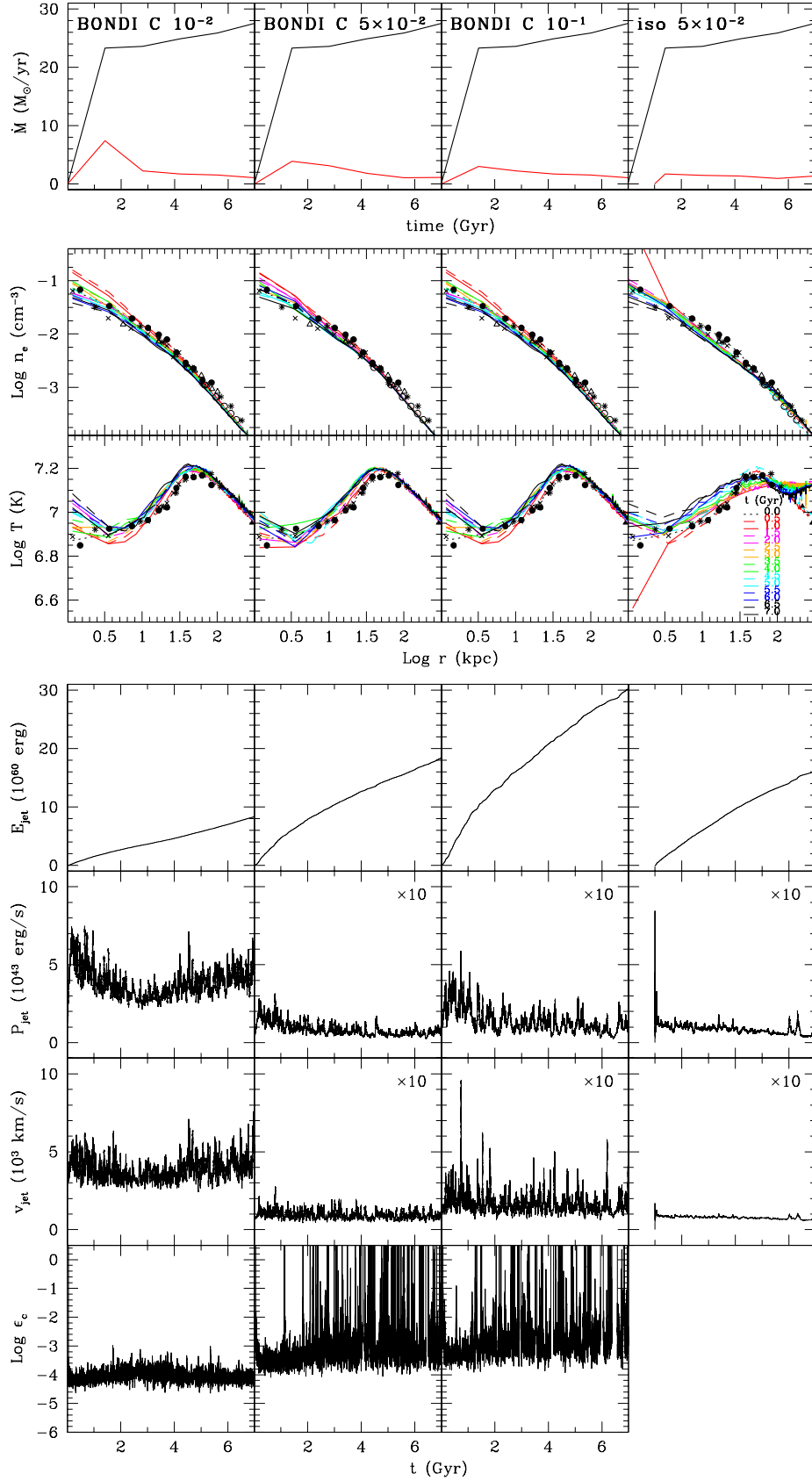
The final injected energy is relatively low,  $\sim 1.8 \times 10^{61} \text{ erg}$  ( $3.6 \times 10^{61} \text{ erg}$  for the bipolar outflow), compared to the total ‘available’ BH energy  $1.8 \times 10^{62} \text{ erg}$ ; roughly estimated as  $E_{\text{BH}} \sim 0.1 M_{\text{BH}} c^2$ , with  $M_{\text{BH}} = 10^9$ . This will be a typical feature of galaxy groups, in contrast to the high input energies of massive clusters, whose models can sometimes exceed the above quantity.

Furthermore, we tested several initial conditions and we concluded that the dynamics and results of our feedback models are, overall, not distorted by relatively different initial temperature and gravity profiles. For example, in Fig. 2 (fourth column), we started the computation with an isothermal profile ( $\sim 1.35 \times 10^7 \text{ K}$ ), retrieving the density structure from a theoretical NFW plus deVaucouleurs potential. After the first Gyr of pure CF, the Bondi feedback ( $\epsilon_B = 5 \times 10^{-2}$ ) is again very effective in quenching the cooling flow and at the same time preserving the cool core appearance.

A possible riddle for all continuous models remains the absence of frequent jet-inflated spherical cavities. The continuous AGN activity (mean  $v \sim 10000 \text{ km s}^{-1}$ ) carves a narrow tunnel of about 30 kpc in length, although its density contrast with the environment is large only for  $z \lesssim 10$  kpc (and not particularly evident in the surface brightness maps; see Sec. 4).

### 3.2.2 Model Bi5em2, $\epsilon_B = 5 \times 10^{-2}$

In a self-regulated (subgrid) mechanism we have to face substantially two problems. The first one is how much power to link to the feedback, while the second one is the right timing, i.e. when to turn on and off the heating machine.



**Figure 2.** Evolution of Bondi (continuous) feedback models with different efficiencies (the latter being the isothermal start). Panels in the first three rows (top to bottom) represent the same quantities as in Figure 1. Panels in the other four rows show: total injected kinetic energy (in the half-space  $z > 0$ ), outflow power and velocity, associated cold efficiency (see text). The label ‘ $\times 10$ ’ means that the units in the ordinate axis have been multiplied by 10.

In the following simulation (Figure 3, third column) we link the activation of the AGN heating to the gas cooling, but use the standard Bondi rate for the gas accretion onto the black hole. In other words, an outflow is generated when  $\Delta M_{\text{cold}} \neq 0$ , with an energy linked to  $\dot{M}_{\text{B}}$  in the usual way.

This feedback scheme tries to reproduce a self-regulated intermittency of the outflows (ideal Bondi models can only be continuous), with cycles of inactivity corresponding to moments of high hot gas entropy. In fact, when the gas begins to cool, it will usually start to flow towards the central black hole.

This way, the temperature profiles are a bit more consistent with the observational data, especially at intermediate radii. Although the jets are intermittent, their frequency is high, a condition that grants the quenching of cooling rate ( $\dot{M}_{\text{cool}} \sim 0.5 - 2 M_{\odot} \text{ yr}^{-1}$ ). The density profiles do not depart from the cool core status, without a strong steepening (central values  $\sim 0.1 \text{ cm}^{-3}$ ).

Bondi accretion rates are almost identical to Bc5em2, with the total energy injected in 7 Gyr being a bit less:  $\sim 1.5 \times 10^{61} \text{ erg}$ . The average jet power is also a factor of  $\sim 1.3$  less,  $\sim 5.5 \times 10^{43} \text{ erg s}^{-1}$ .

This model clearly solves the problem of jet-inflated cavities in the IGM. The outflows duty cycle<sup>5</sup> is roughly 80-85 per cent (in the whole computation). The pattern is not very regular, in fact the cycle is more frenetic between 2 and 5 Gyr, when the central gas has been heated efficiently. Every time the jet (with velocities usually of  $8000\text{--}10000 \text{ km s}^{-1}$ ) turns on again, a bubble of small size ( $10 - 15 \text{ kpc}$ ) is seen in the density map. Note that after a period of quiescence the subsequent injection produces a peak in the power, promoting the above mentioned cavity inflation through shock heating. The side effect consists in more evident perturbations in some  $T$  profiles (e.g. 3 and 7 Gyr), however still compatible with typical galaxy group observations.

Finally, during runtime we calculated, at every timestep, the efficiency ( $\epsilon_c$ ) that would have the cold feedback mechanism (bottom panel). The result is striking: on average, the two schemes are almost coincident with  $\epsilon_c$  around  $10^{-3}$ , except for few short timesteps, in which the cold feedback requires a 100 per cent efficiency (because the cooled mass is almost zero).

### 3.2.3 Model Bc1em1, $\epsilon_{\text{B}} = 10^{-1}$

We begin now to describe models from higher to lower efficiencies, alternating again continuous and intermittent Bondi methods.

The following simulation is very computationally expensive, because the (continuous) outflow velocity rises often over  $20000 \text{ km s}^{-1}$ . It is shown in Figure 2, third column. The cooling rate is quenched to fraction of  $M_{\odot} \text{ yr}^{-1}$  after just a few Gyr. The total injected energy is  $3 \times 10^{61} \text{ erg}$  (about 1.5 times greater the intermittent counterpart, next model Bi1em1). The consequence of this high energy deposition is a progressive steepening in the temperature gradient,

<sup>5</sup> The common duty cycle retrieved by observations can be quite different from our numerical estimates, because the definition of an ‘active’ AGN highly depends on some luminosity threshold (in the X-ray, radio, etc.) and on the properties of the sample.

with a moderate spike in the inner 4 kpc, where the jet is always active. During some timesteps the outflow reaches  $5 \times 10^{44} \text{ erg s}^{-1}$ , a quite strong power for Bondi accretion.

The compared efficiency analysis (bottom panel) shows that a cold feedback triggering could not even be possible in 20-30 per cent of the evolution, because it would break the unity threshold. In the other periods it would be associated with a value around  $2.5 \times 10^{-3}$ .

### 3.2.4 Model Bi1em1, $\epsilon_{\text{B}} = 10^{-1}$

The following (Fig. 3, fourth column) is another computationally expensive model, which touches the limit of acceptability in the parameter space, for Bondi models. The timing is again associated with the cold gas. The cooling rate is very similar to the precedent continuous model (Bc1em1), with the reasonable range of  $0.5\text{--}1.5 M_{\odot} \text{ yr}^{-1}$  range, declining at late times. The density profiles are optimal, not altered from the initial data. Temperatures start to feel the strong outbursts, which have sometime power in excess of  $10^{45} \text{ erg s}^{-1}$  (with velocity larger than  $2 \times 10^4 \text{ km s}^{-1}$ ). In fact at later times the central gas is heated up to  $10^7 \text{ K}$ , during some event.

The associated cold efficiency has a common trend around  $2.5 \times 10^{-3}$ , but with many oscillations after 3 Gyr, reaching easily unity. Notice that these moments last very few timesteps, after which  $\epsilon_c$  reset to lower values (in contrast to a first impression of the tight plot).

### 3.2.5 Model Bc1em2 and Bi1em2, $\epsilon_{\text{B}} = 10^{-2}$

When the efficiency is lowered to  $\epsilon = 10^{-2}$  the heating provided by the feedback is considerable ( $\sim 8 \times 10^{60} \text{ erg}$ ). This decreases the cooling rate down to at least 30-40 per cent of that of the pure CF (Figure 2, first column). The profiles are close to the observed data, thanks to an always continuous outflow with velocity  $4 - 5 \times 10^3 \text{ km s}^{-1}$  and power  $4 - 5 \times 10^{43} \text{ erg s}^{-1}$ .

The intermittent simulation is very similar to the continuous evolution (Fig. 3, second column), except that, initially, the system is permitted to cool. Without this early opposition, the outflows - with same power - can not halt the cooling so efficiently like in the previous case. The feedback finds an equilibrium only at 4 Gyr, while at later times it will slowly increase, on the contrary of a reasonable self-regulated model.

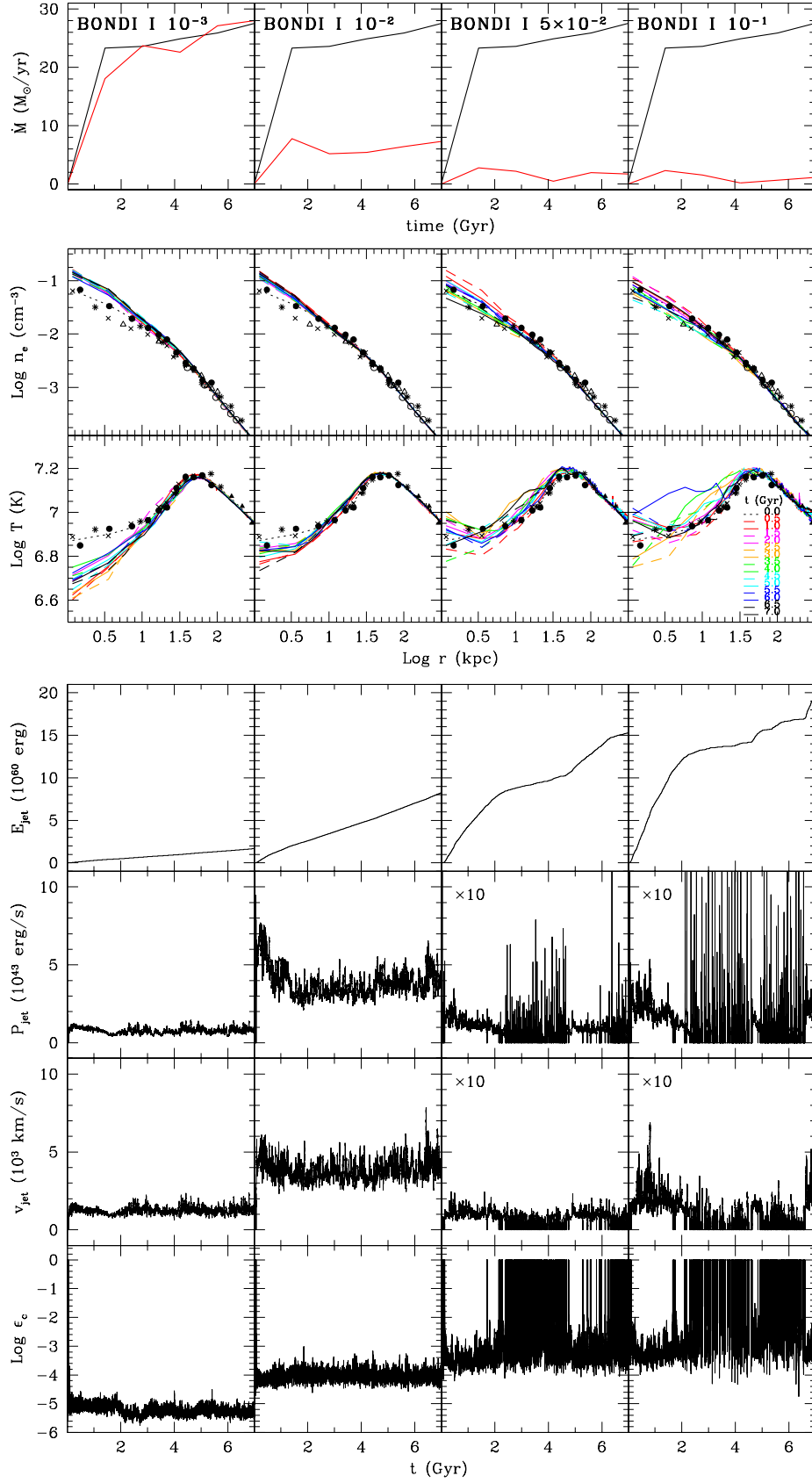
The associated efficiency of a  $\Delta M_{\text{cold}}$  model is near  $10^{-4}$ . In fact, we will see that the linked cold feedback model will produce an almost identical outcome, i.e. weak heating (Fig. 4, second column).

### 3.2.6 Model Bi1em3 (or Bc1em3), $\epsilon_{\text{B}} = 10^{-3}$

As a template for a typical weak model, a simulation with Bondi efficiency of  $10^{-3}$  produce a cooling rate, which is identical to a pure CF run:  $\sim 25 - 26 M_{\odot} \text{ yr}^{-1}$  (Fig. 3, first column).

The only clue for the presence of AGN heating is that the profiles do not suffer a heavy decline with time, even if they possess a remarkable steep gradient ( $T$  down to  $4 \times 10^6 \text{ K}$ ).





**Figure 3.** Evolution of Bondi (intermittent) models with increasing efficiencies, from left to right. The description of the plots are same as for Fig. 2.

The outflow is always continuous (the model could be also named Bc1em3), with a very low velocity around  $1000 \text{ km s}^{-1}$  and a power often under  $10^{43} \text{ erg s}^{-1}$ . There is no possibility that this model will become intermittent at any time, due to the constant central cooling.

### 3.3 Cold Feedback ( $\Delta M_{\text{cool}}$ regulated)

#### 3.3.1 Model C5em5, $\epsilon_c = 5 \times 10^{-5}$

The results presented in the previous Section for the Bondi accretion models suggest that, compared to galaxy clusters, groups require lower efficiencies of at least a factor of 10. Therefore, we start illustrating the cold feedback mechanism for the lowest adopted  $\epsilon_c$  and then moving to more efficient outflows.

Here we still use the entrainment injection method, with width and length of the active region 1 and 2 kpc (2 and 4 grid points), respectively. In G11, in fact, we concluded that the size of the jet and the type of injection do not change drastically the evolution of the feedback.

As shown in the first top-left panel of Figure 4, the cooling rate settles on a steady value around  $\sim 10 \text{ M}_{\odot} \text{ yr}^{-1}$ . This rate is obviously unacceptable, although reduced to the  $\sim 50\%$  of the pure CF model value. With such a low efficiency, the azimuthally averaged, mass weighted temperature and density profiles are only slightly modified by the heating and do present the excessive accumulation of gas near the center, typical of the CF model. In the center the temperature is  $\sim 5.6 \times 10^6 \text{ K}$  and the numerical densities  $\sim 0.18 \text{ cm}^{-3}$ .

The outflows, typically have a power of  $4 - 5 \times 10^{43} \text{ erg s}^{-1}$  and a velocity of  $3000 - 4000 \text{ km s}^{-1}$ . The total injected mechanical energy is in fact quite low,  $6 \times 10^{60} \text{ erg}$ , and the outflows are almost continuous, because they are never able to stop the cooling flow. Given the rare period of inactivity, the ‘duty cycle’ is  $\sim 95$  per cent.

At the end of the simulation  $6 \times 10^{10} \text{ M}_{\odot}$  have cooled and dropped out of the hot phase. The vast majority of gas cools at the very center. If all the cooled gas were accreted onto the central black hole, as we have simplistically assumed in this scheme, the final BH mass would result about an order of magnitude greater than the expected one. In principle, we could avoid the problem of the excessive black hole mass by assuming that only a fraction of the cooled gas actually accretes on it with a higher efficiency (see Sec. 3.6, InOut models).

#### 3.3.2 Model C1em4, $\epsilon_c = 10^{-4}$

As anticipated, the next step is to increase the efficiency, in order to find a more suitable heating power.

In the following model, where the efficiency increased by a factor of five,  $\epsilon_c = 10^{-4}$  we obtain in fact a jet power of  $\approx 10^{44} \text{ erg s}^{-1}$  and velocity oscillating around  $5000 \text{ km s}^{-1}$  (see Fig. 4, second column). However, the cooling rate is only slightly reduced to  $6 - 7 \text{ M}_{\odot} \text{ yr}^{-1}$  and radial profiles tend to be similar to the ones of previous model. The difference is that now the curves decline at 6 kpc, instead of 10 kpc. Evidently, the outflows deposit their energy in more inner zones.

We conclude that, even if the total injected energy

reaches almost  $10^{61} \text{ erg}$ , at this stage the cooling flow is not quenched in a successful manner. This is also underlined again by the almost continuous presence of the outflows.

#### 3.3.3 Model C5em4, $\epsilon_c = 5 \times 10^{-4}$

At  $5 \times 10^{-4}$  we finally recover a successful heating evolution. As in previous computations, at early time (first Gyr) the radiative cooling prevails over the outflow mechanical heating and the cooling rate reaches a peak of  $4 \text{ M}_{\odot} \text{ yr}^{-1}$ . However the long term evolution presents different intriguing results. After 2 Gyr the system becomes much more turbulent and chaotic, inducing a reasonable amount of mixing, that permits the gas circulation and reheating in a very efficient way, also in the 5 kpc nucleus.

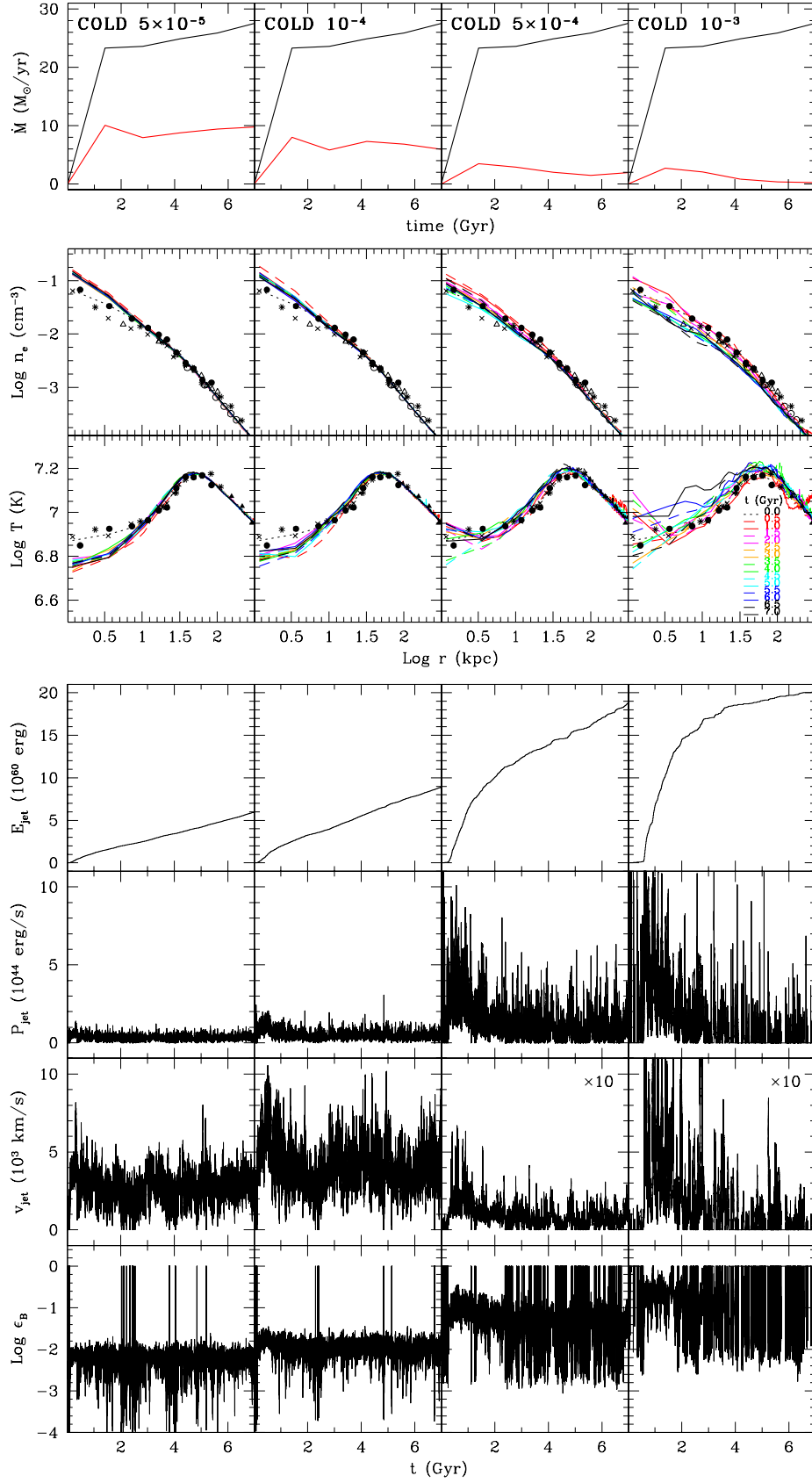
As shown in the third column of Fig. 4, the temperature in that region is almost constant, with values close to that observed for NGC 5044 ( $\approx 8 \times 10^6 \text{ K}$ ; Buote et al. 2003; David et al. 2009). This very important feature is also described by the density curves: a gradual flattening of the central profile is seen through the entire evolution. It is striking that the 7 Gyr (black) profile is practically superposed to the initial fit. At that time (redshift = 0) the cooling rate is  $\sim 2 \text{ M}_{\odot} \text{ yr}^{-1}$ , about 7% of the pure CF run, a significant suppression which brings the value of  $\dot{M}_{\text{cool}}$  in reasonable agreement with the observations (David et al. 2009; Buote et al. 2003; Tamura et al. 2003).

The shock waves generated by the outflows, with power usually between  $\sim 2 - 5 \times 10^{44} \text{ erg s}^{-1}$ , are not strong enough to significantly alter the global positive temperature gradient, although small amplitude ripples are present. These waves correspond to weak shocks associated with the jet propagation and are visible up to a distance of  $\sim 300 \text{ kpc}$ . They are not so evident as in galaxy clusters because the energy involved here are two or three orders of magnitude lower. In fact the total jet energy is  $1.8 \times 10^{61} \text{ erg}$ . The gas is typically ejected with  $v_{\text{jet}} \sim 10^4 \text{ km s}^{-1}$ .

Furthermore, an important difference between clusters and groups is the duration of each event. In cluster models, a duty cycle of 0.1 was quite usual, because the very short super-Eddington bursts could stop instantly the cooling flow, with the consequence of perturbed profiles, near the ignition time. Here, our estimated duty cycle is roughly 0.85. Therefore the situation is reversed: successful cold feedback models in groups require an almost continuous heating, with short pauses of tens Myr.

Notice that the Eddington luminosity,  $L_{\text{Edd}} \approx 1.5 \times 10^{38} (M_{\text{BH}}/M_{\odot}) \sim 10^{47} \text{ erg}$  (for a  $10^9 \text{ M}_{\odot}$  black hole), is far above the regime of the current model. In fact the accretion rate oscillates between  $10^{-3} - 10^{-2}$  the Eddington rate. As seen in Section 3.4, a  $L_{\text{Edd}}$  jet can easily erase the cool core structure of the group.

In summary, the analysed behaviour of C5em4 seems to be similar to that the quiet Bondi feedback. In the bottom panel we have calculated, at every timestep, the associated Bondi accretion rate and the required  $\epsilon_B$  to reproduce the same instant mechanical energy. As a striking result, a Bondi efficiency of  $\sim 5 \times 10^{-2}$ , especially after 2 Gyr, is retrieved from this analysis. Only in a few events, the cold mechanism detaches from the regular regime of Bondi, because of its intrinsic impulsivity. Nevertheless the similitude is quite evident and indeed, if we compare the two outcomes of both



**Figure 4.** Evolution of all cold accretion models with increasing efficiencies, from left to right. The description of the plots are same as for Fig. 2.

models (especially intermittent Bondi, Fig. 8, third column), they appear deeply connected also in a quantitative manner.

### 3.3.4 Model C1em3, $\epsilon_c = 10^{-3}$

Increasing the efficiency by a factor of 2 generates another positive model, with some features approaching the borderline of a violent disruptive heating.

In fact, with a jet power up to  $10^{45}$  erg s $^{-1}$ , the cooling flow is perfectly stifled, asymptotically decreasing to a fraction of  $M_\odot$  yr $^{-1}$  after a few Gyr (Fig. 4, fourth column).

The beginning of the violent regime is quite evident in the averaged profiles, which now tend to oscillate in a large  $\sim 50$  kpc region. Overall, the cool core is conserved, but the temperature indicates some overheating in the nucleus at later times.

With our adopted active region, in a few outbursts, the velocity is greater than  $10^5$  km s $^{-1}$  line, while the outflow mass rate is several tens  $M_\odot$  yr $^{-1}$ , as in all previous  $\Delta M_c$  models. This is a clear indication that at higher efficiencies we will approach a relativistic regime and a catastrophic heating (we will not show here results for  $\epsilon_c > 10^{-3}$  but see fig. 5 of G11 for an analogous model for clusters). The equivalent Bondi efficiency for model C1em3 is sometimes 0.5 or more, difficult to justify.

The total injected energy of C1em3 is similar to the previous successful model, a sign of a good self-regulation in the global feedback process. This energy can be compared with the total energy radiated away,  $\approx 1.38 \times 10^{60}$  erg (in the simulated half-space  $z > 0$ ). Interestingly, the present heating provides more energy than that lost by radiation ( $E_{\text{rad}} \sim 1.4 \times 10^{60}$  erg). Notice that, in every described model, the total outflow energy (for the full-space system) is about an order of magnitude lower than the available BH energy ( $\sim 1.8 \times 10^{62}$  erg). The evolution of the energetics is very similar to the description presented by G11. The core kinetic energy increases after every intense AGN outburst, but it is soon dissipated and transformed into potential energy through the expansion of the IGM.

## 3.4 Intermittent feedback

### 3.4.1 Model Int510m: $10^{-4} P_{\text{Edd}}$

In this series of models we want to decouple the simulation from the self-regulation engine, in order to control some important AGN outbursts parameters. For example, it is interesting to fix the frequency of the outflows. In G11 we found that intermittent outflows, with jet duration of 5 Myr and activated every 10 Myr, are very effective in inhibiting gas cooling preserving the correct temperature and density profiles in galaxy clusters. This AGN activity cycle agrees with observations of acoustic ‘ripples’ in Perseus cluster (e.g., Fabian et al. 2006).

In the models described in this Section we do not insert an ad hoc velocity, but we retrieve its value from setting a constant power, here taken equal to  $10^{-4} P_{\text{Edd}}$ . Thus  $P_{\text{jet}} \sim 4 \times 10^{43}$  erg s $^{-1}$ . We choose the ‘nozzle’ injection method, therefore the velocity is constant: 7000 km s $^{-1}$ . Note that the efficiency is irrelevant in the computation.

As a result (Fig. 5, first column), the cooling rate is less than a few  $M_\odot$  yr $^{-1}$ , for several Gyr, and shows a slow

increase after 4.5 Gyr, up to  $4 M_\odot$  yr $^{-1}$ . The azimuthally averaged density profiles are almost superposed to the observations, with a slight decrease in time, becoming flatter.

Thus, like in Bondi models, the radiative cooling is significantly reduced by the simulated heating process. Using the nozzle injection (essentially an outflow with negligible height) produce a spike in the very few kpc, while at radii greater than 10 kpc the fluctuations from initial  $T(r)$  are almost zero. As expected, shock heating is more vigorous in the nucleus when the outflow is injected through the boundary, while more effective at intermediate radii, when the entrainment method is adopted.

In this type of intermittent models it is not granted that the feedback produces evident cavities. In fact with a cycle of 5-10 Myr the head of the jet cocoon almost touches the backflow tail of the last bubble. Thus, we expect that with a duty cycle greater than 50 per cent the jet becomes practically continuous.

### 3.4.2 Model Int510h/l: $10^{-3}$ and $10^{-5} P_{\text{Edd}}$

Keeping the same cycle scheme (5-10 Myr), but increasing the power by a factor of 10 produces a typical ‘exploding’ simulation (not shown). The temperature profile gets a very steep negative gradient, as soon as the outflow ignites, destroying the entire cool core and generating a ‘plateau’ in  $n(r)$ . The cooling rates are obviously zero, but with unacceptable observables.

On the other hand, with a much lower power ( $4 \times 10^{42}$  erg s $^{-1}$ )  $\dot{M}_{\text{cool}}$  approaches  $12 M_\odot$  yr $^{-1}$  after just 1 Gyr. Generated bubbles are quite stable and, being slowly inflated, show cold rims in the early phases. Nevertheless, the density and temperature profiles resemble those of a classical cooling flow, with less peaked gradients.

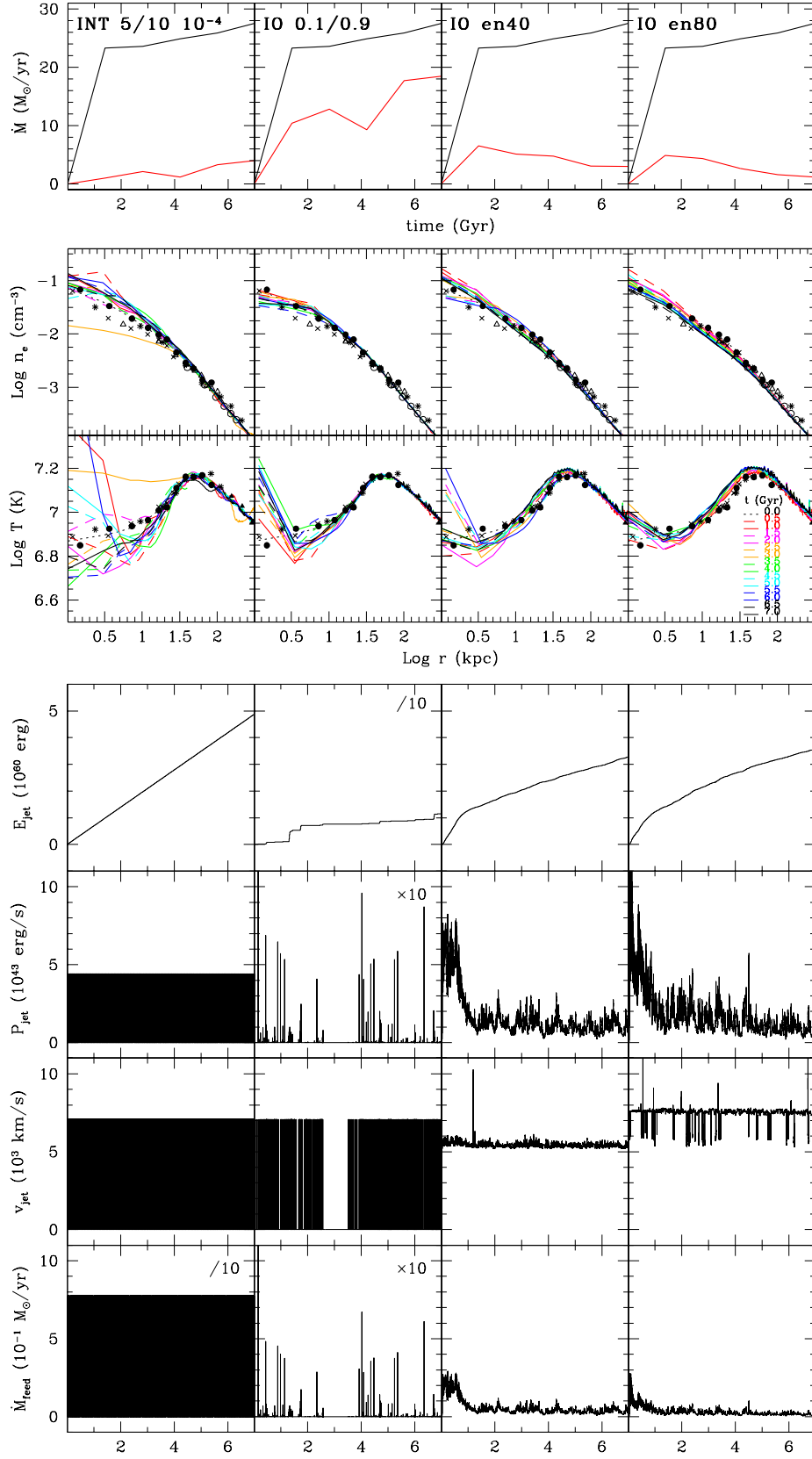
We can conclude that, even with fixed intermittency, an acceptable AGN feedback model should not approach an Eddington regime (like proposed in some analytical works, e.g King 2009), at least in galaxy groups, where a strong burst can easily wreck the delicate thermodynamic structure of the core.

### 3.4.3 Varying fixed cycle: 1-10, 2.5-10, 3.3-10, 7.5-10

Keeping a fixed jet power, as in our acceptable model Int510m, but this time varying the duration of the AGN activity, leads to models that must be rejected.

Indeed, when every outflow event has a duration of 1, 2.5 or 3.3 Myr the intermittent feedback becomes quite ineffective in halting the inflowing cold gas: the central gas density slowly grows with time until radiative cooling prevails over heating, causing the cooling rate to surpass the threshold of acceptability. For example after just 1 Gyr, with 3.3 Myr duration, the cooling rate is over  $7 M_\odot$  yr $^{-1}$  and the temperature curve turns very similar to those of model CF.

On the contrary, when the jet duration exceeds 5 Myr the inflated cavities disappear, because the different outbursts melt rapidly in a ten kpc zone, producing an almost continuous injection. The consequence is a steep  $T$  gradient at the center, which can halt the cooling flow, but without self-regulation it easily overheats the system.



**Figure 5.** Evolution of intermittent and InOut models (with or without mass loading). The description of the plots are same as for Fig. 2.

### 3.5 Thermal feedback

#### 3.5.1 Adding thermal energy: 20% up to 99%

It is worth noting that one difficulty of a pure kinetic outflow (often called ‘momentum-driven’) is that it can easily carve a tunnel in the surrounding IGM if the ram pressure of the jet ( $\rho_j v_j^2$ ) is much larger than the thermal pressure ( $\rho c_s^2/\gamma$ ) of the gas. Thus a feedback with high kinetic energy will advance undisturbed in the group core, depositing its energy at intermediate radii (15 – 30 kpc). At the base, the cold gas accumulates in a torus-like manner. This is especially evident at early stages of a momentum-driven outflow. The successful models, we found, are able to quench cooling flow, because at some point the generated turbulence induces strong mixing in the gas, also in the very center. Therefore the circulation inside the jet path makes shock heating very effective. In our models the turbulence is sustained only by the AGN feedback. It is likely that this process dominates in the very central region of the system, although turbulent and bulk motions caused by cosmological accretion, usually very subsonic, may also contribute (e.g., Heinz et al. 2006).

Nevertheless, the high density gas in the torus cools efficiently and triggers the AGN feedback in an almost continuous way. It is physically reasonable that a part of the jet power is converted in thermal energy, especially during the entrainment process. Based on these considerations, we simulated some models with a fraction of the total injected energy in the form of thermal energy, through the nozzle. We kept the Bondi prescription for the feedback method.

As pedagogical purpose, we first set the fraction of  $E_{\text{th}}$  as 99 per cent the total energy. This setup is similar to the model of Cattaneo & Teyssier (2007) with loading factor of 100 and Bondi efficiency 0.1. As expected, the first powerful outflow (over  $10^{44}$  erg s $^{-1}$ ) destroys the entire thermodynamic structure of the cool core: the produced shock (with temperatures above  $10^{10}$  K) is almost spherical. This is another indication that the group necessitates a much more delicate heating compared to a cluster. Lowering the efficiency to  $10^{-3}$  still generates a similar catastrophic heating.

On the other hand, keeping the above efficiency, but reducing the fraction of  $E_{\text{th}}$  to 20% or 33% results in models overall similar to purely kinetic ones. One major difference are small puffs at the base of the jet, that enable more turbulence. The problem is that, in the inner 8 – 10 kpc, temperature profiles show a spike, due to injected  $E_{\text{th}}$ . Another interesting effect is the enlargement of the tunnel carved by the outflow, because of the increased internal pressure, compared to the momentum-driven one.

The best model seems to be Eth50 (not shown), with 50% thermal energy and efficiency  $5 \times 10^{-3}$ . The feeble jet is almost always continuous, with velocity 3000 km s $^{-1}$ , but the thermal energy injection generates a break-up in the jet structure, which fragments in small buoyant bubbles of size 5 – 8 kpc; a very interesting feature that is seen in NGC 5044 (David et al. 2009, 2010).

We conclude that a good fraction of thermal energy associated with the AGN feedback can help the deposition of heating at very small radii, reducing the cold torus at the base of the jet and fragmenting the outflow in small size bubbles. At the same time, however, it is difficult to obtain

a flat or positive (mass-weighted)  $T$  profile. We will expand this analysis in a future work, with very high resolution.

### 3.6 In & out feedback

#### 3.6.1 Model IO1-9

One problem of self-regulated feedback models is how much of the gas contributes to the growth of the black hole mass. Needless to say, with a resolution of  $\sim 500$  pc we cannot consistently estimate the accretion rate onto BH. As noted in some works (e.g., Cattaneo & Teyssier 2007; Ostriker et al. 2010; G11) part of inflowing gas onto a black hole could be thrown back by the generated outflow, perhaps through entrainment. Therefore only a fraction of the accreting mass,  $\Delta M_{\text{acc}}$ , might actually be captured by the black hole. From another perspective, we can see this as a reduced total efficiency.

That being stated, we computed some models in which we attempt to track the part ( $f_{\text{in}}$ ) of infalling gas that really increases the BH mass. The residual fraction ( $f_{\text{out}} = 1 - f_{\text{in}}$ ) is considered the active mass of the outflow:

$$\frac{1}{2} f_{\text{out}} \dot{M}_{\text{acc}} v_{\text{jet}}^2 = f_{\text{in}} \epsilon \dot{M}_{\text{acc}} c^2. \quad (10)$$

Note that in these models it is better to use the nozzle injection mode, in order to totally control the outflowing mass, without altering the internal domain.

An interesting feature of this method is that the outflow velocity is practically constant, dependent on  $f_{\text{in}}/f_{\text{out}}$  (and  $\epsilon$ ). An observational constrain of the outflow velocity may thus give hints about this ratio between infalling and outflowing matter.

Setting  $f_{\text{in}} = 0.1$  ( $f_{\text{out}} = 0.9$ ) and efficiency  $10^{-3}$ , the outflow, coming out of the nozzle, has a velocity around 7000 km s $^{-1}$ . With cold accretion, the power of the jet presents strong oscillations between  $10^{43}$  and  $10^{45}$  erg s $^{-1}$  while the cooling rate approaches in a few Gyr the pure CF simulation. Even with Bondi accretion (same efficiency; Fig. 5, second column), which, in theory, is more regular, the (high) outflow power can not find a stable balance in time, resulting in  $\dot{M}_{\text{cool}} \sim 18 M_{\odot} \text{ yr}^{-1}$  at 7 Gyr. While some accretion events reach 4-5  $M_{\odot} \text{ yr}^{-1}$ , the produced strong feedback does not last long enough. In fact the total injected energy is very low:  $10^{59}$  erg. It is interesting that the radial profiles of this model (IO1-9) show a cool core, with the exception of a central negative temperature gradient. Therefore, overall acceptable mean  $T$  and  $n$  profiles do not necessary imply that the system is not cooling.

Trying to increase the efficiency is a serious problem for the InOut model, because the velocity will constantly overtake 50000 km s $^{-1}$ . We could lower  $f_{\text{in}}$  in order to increase the jet mass, but with just 1 per cent of accreting mass (probably unrealistic) the velocity will still have very large values.

#### 3.6.2 Model IOen40 and IOen80

The only solution, we have found, is to return back to the ‘entrainment hypothesis’ and multiply  $f_{\text{out}}$  by a factor  $\eta$  (like a mass loading factor). Following this assumption, with  $\eta = 40$  and  $f_{\text{out}} = 0.3$ , we could enhance the Bondi efficiency

( $\epsilon = 5 \times 10^{-3}$ ) to obtain an acceptable cooling rate, below  $5 \text{ M}_\odot \text{ yr}^{-1}$  (Fig. 5, third column), after the small bump at 1.5 Gyr. Now the velocity has a value of  $\sim 6000 \text{ km s}^{-1}$ . With  $\eta = 80$  the average cooling rate is further reduced, asymptotically decreasing to  $1 \text{ M}_\odot \text{ yr}^{-1}$  (fourth column). Both simulations generate some of the best radial profiles, which keep the cool core appearance for the entire evolution time, almost ‘glued’ to the initial (observed) condition. This is an indication that the feedback has returned stable (around  $P_j \sim 1 - 3 \times 10^{43} \text{ erg s}^{-1}$ ), gentle and continuous, very similar to successful Bondi models (Sec. 3.2). Notice that the accretion rate is again sub-Eddington.

Overall, a pure InOut model exhibits a spasmodic behaviour, because of the intrinsic linking between accreting and outflowing matter, which can be smoothed out only by introducing a mass loading factor. However, this parameter is nowadays unknown and therefore its value is chosen ad hoc, in order to retrieve reasonable jet velocities. It is therefore simpler and cleaner to adopt the usual entrainment feedback of the main models (Sec. 3.2 - 3.3), seeing that the results are analogous.

#### 4 DYNAMICS AND OBSERVABLES

In this Section we will show the ‘real face’ of the best simulated models, at some relevant times. We will analyse physical quantities, such as gas density, and other astronomical observables, i.e. integrated emission-weighted maps. Notice that the entire structure of our computation favours the study of a very long term evolution. In order to fully comprehend the dynamics of single burst events, we should carry on a short term evolution with much higher resolution. We will confront this setup in a future dedicated paper.

In Fig. 6 the first column exhibits two-dimensional density cuts through the  $x$ - $z$  mid-plane (panels a-d) with the velocity field superposed. The first row is associated with Bc5em2 model (at 5 Gyr), one of the successful models in our set of simulations. This snapshot depicts one of the three typical stages of the AGN-regulated simulation in a galaxy group. The gentle and continuous heating of the outflow ( $\sim 10^{44} \text{ erg s}^{-1}$ ) carves a narrow tunnel in the intragroup medium with electron density around  $2 \times 10^{-4} \text{ cm}^{-3}$ . The diameter of the channel is usually 4-5 kpc, collimated in the inner region by the thermal pressure of the surrounding gas. At 14 kpc, where the jet ram pressure becomes comparable to the thermal pressure of the ambient gas ( $P_{\text{th}} \sim 2.5 \times 10^{-11} \text{ erg cm}^{-3}$ ), the outflow structure becomes perturbed and more turbulent<sup>6</sup>. In fact, near the tunnel, instabilities are visible, a signature of further IGM entrainment and turbulent mixing. The latter has a relevant role in the feedback process, especially at later times, when the AGN has been active for several Gyr (Fig. 2, cooling rate decreases with time). In fact, even if the turbulent mixing does not directly heat the gas, it greatly favours the deposition of energy at the base of the jet, where the cooling tends to dominate.

The fact that the global cool core appearance is not greatly modified, is another key result. Although the continuous outflow generates a tunnel, the overall initial structure

is conserved. On the other hand, increasing the efficiency of Bondi models leads to a wider V-shape channel, which begins to dominate the core of the group. This is not observed and in fact those models are rejected also for the central negative  $T$  gradient. As seen in the second column (panel e), the (emission-weighted) temperature of Bc5em2 has instead a positive gradient, almost flat in the 5 kpc nucleus.

The continuous presence of the channel (interrupted sometimes by the fragmentation) is a feature not commonly seen in real groups, at least in the local universe<sup>7</sup>. However, in the third column (panel i) the X-ray surface brightness map does not show an evident channel, with only two very faint features (at 12–16 kpc), similar to a pair of ‘arms’. Going into quantitative details we performed one dimensional (1D) cuts through  $z$  of  $\text{SB}_X$  at different levels (from 4 up to 20 kpc; see Fig. 7, non-black lines). It is clear that the central depressions are not deep (15 – 20%, usually with a difference of  $5 \times 10^{-6} \text{ erg s}^{-1} \text{ cm}^{-3}$ ), plus the width is particularly slim (few kpc), making the detection of the channel extremely difficult<sup>8</sup>. Over 20 kpc the slim tunnel is lost in the integration trough line of sight.

The last column is associated with the tracer of the iron abundance (again emission-weighted), injected by SNIa and stellar winds of the cD galaxy (see G11 for details). This type of advected quantity is deeply linked to the history of the AGN heating. In panel o is indeed possible to recognize the outflow pattern, which is asymmetrical and can drag the metals produced deep inside the central elliptical galaxy up to 15-20 kpc, with values around  $0.3 - 0.4 \text{ Z}_\odot$ . This characteristic is commonly observed in the core of AGN heated systems (e.g. Kirkpatrick et al. 2009, 2011; Rasmussen & Ponman 2009; David et al. 2010; Doria et al., in preparation).

The second row of Fig. 6, shows another good model, one based on the cold feedback. C1em3 (at 0.5 Gyr) shows the other face of the AGN-regulated evolution: an AGN burst with power  $\sim 1.2 \times 10^{45} \text{ erg s}^{-1}$  generates a big cavity in the IGM density, with major/minor axis of 16/10 kpc. The injected energy is almost  $10^{60} \text{ erg}$ , with an outflow velocity over  $10^4 \text{ km s}^{-1}$ . The buoyant bubble has a high density contrast with the environment,  $\sim 100$ .

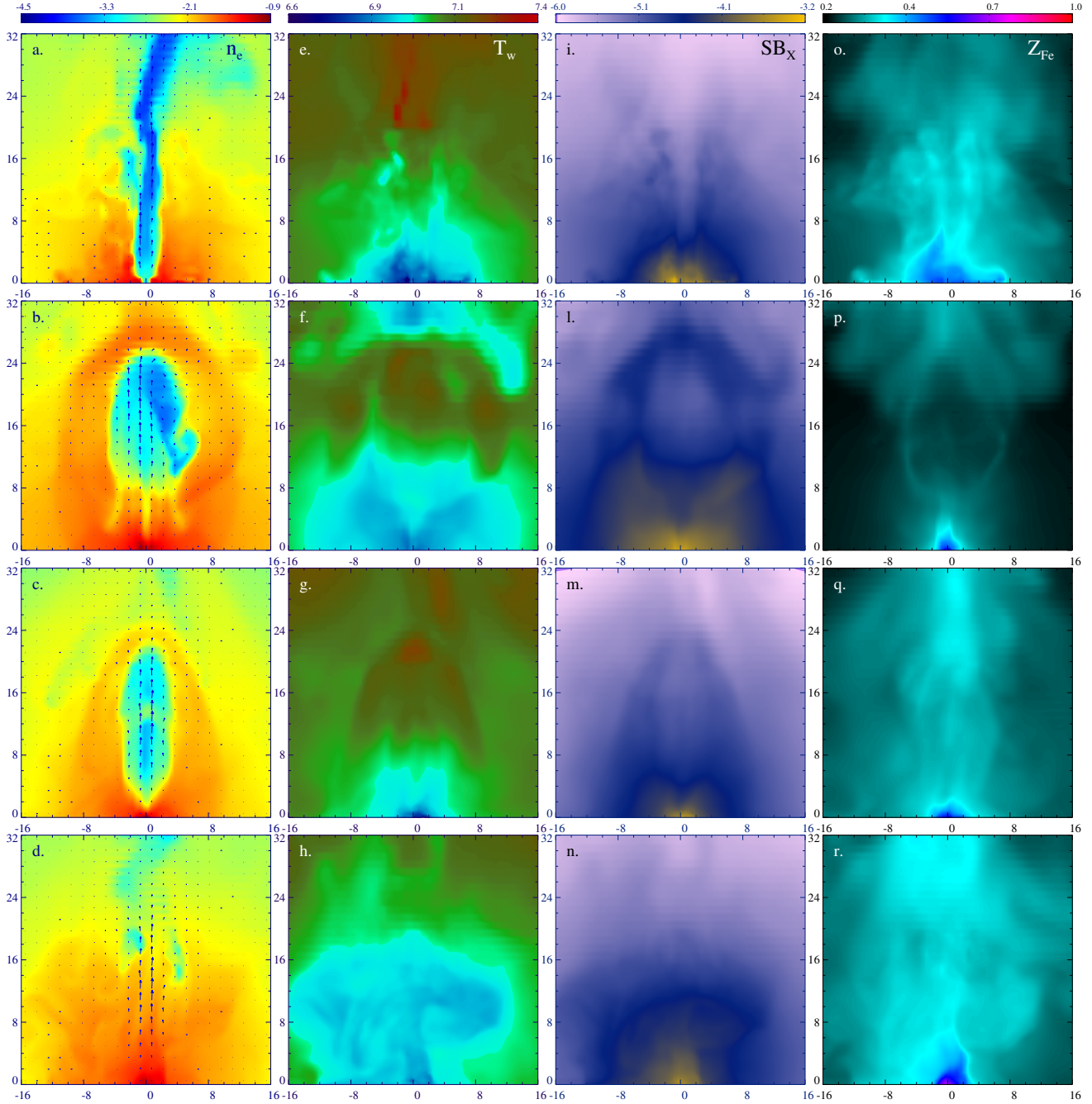
In contrast to the violent cavities generated in our previous galaxy cluster simulations (G11), the cold accretion mechanism is able to inflate low density cavities without heavy shocks. The outflow power is in the group simulations several orders of magnitude lower and the injection per timestep is usually smoother. In fact (see panel f and Fig. 7, black line of bottom panel),  $T_w \sim 1.45 \times 10^7 \text{ K}$  inside the shell which is only slightly larger than the surrounding gas value. This is also suggested by the homogeneity of the map above 12 kpc (reddish colours).

A striking feature, usually hard to detect, is the bright rim, that surrounds the cavity (panel l). The rim, especially the low- $z$  region, is formed by low-entropy gas originally in the center. This feature is often seen in deep X-ray observations (e.g. Salomé et al. 2006 and references therein),

<sup>6</sup> At 24 kpc the outflow is almost stopped by the IGM, generating a rise in temperature,  $\sim 1.55 \times 10^7 \text{ K}$  (see also Fig. 7).

<sup>7</sup> The evolution of groups is still far to be certain, lacking a complete sample at intermediate and high redshift.

<sup>8</sup> In addition, Poisson noise, background, resolution, and response of the X-ray detector (not present in our mock maps) could easily alter or obscure this very faint and narrow feature.



**Figure 6.** Maps of four best models (kpc unit). Columns, from left to right: cuts through  $x$ - $z$  mid-plane of electron number density ( $\text{cm}^{-3}$ , logarithmic) with velocity field superimposed; emission-weighted temperature maps (K, logarithmic); X-ray surface brightness maps ( $\text{erg s}^{-1} \text{cm}^{-2}$ ); emission-weighted iron abundance maps ( $Z_{\odot}$  unit). Rows, from top to bottom, are associated with different models: Bc5em2 (5 Gyr), C1me3 (0.5 Gyr), Bi5em2 (7 Gyr), Bi1em1 (6.5 Gyr). The colour scale is given by each bar at the top.

suggesting that the rims are colder than the average ambient medium. The 1D cut through  $z = 20$  kpc (Fig. 7) clearly confirms the presence of this kind of rim, a drop of temperature (about 40%) coincident with the high X-ray emission (at  $x = \pm 6$  kpc).

In panel p we show the (emission-weighted) iron abundance map in the  $x - z$  plane. The iron-rich core, few kpc in size, is clearly visible. At  $z \sim 28$  kpc there is a region of Fe-rich gas, lifted by the outburst. The dense cavity rims also have a slightly larger abundance than the ambient gas,

also revealing that the origin of a part of the rim material is connected to the nucleus of the group.

The  $\text{SB}_X$  inside the cavity (panel l) exhibits a depression of  $\sim 50$  per cent with respect to the rims. Notice how this feature (Fig. 7, black line) would be easily detectable in the X-ray, compared to the vanishing faint channel, due to its deep depression and large width. Moreover, the nucleus (5-8 kpc) dominates the emission, while the upper part of the bubble vanishes rapidly in the background ( $> 30$  kpc). The future of this bubble is to buoy outwards and being



destroyed, after few tens Myr, by the backflow and instabilities.

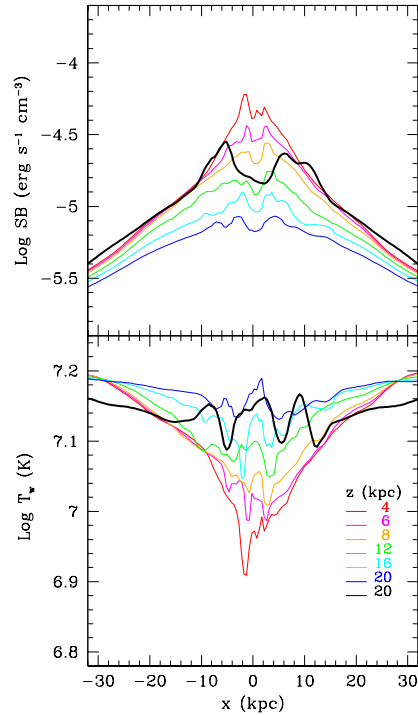
The third row presents the snapshots of model Bi5em2 at 7 Gyr. At that stage of evolution the IGM has accumulated more turbulence, after several AGN events, promoting the diffusion of iron in a radius of 20 kpc from the center (panel q). However, this particular moment is again dominated at the bottom-center by another AGN outburst ( $2 \times 10^{43}$  erg s $^{-1}$ ). Therefore, the young bubble (panel c) still buoys undisturbed in the IGM, generating a slight asymmetry in the iron distribution along jet axis, over the more uniform background.

At this time we caught indeed the early injection phase of the outflow. A quasi cylindrical cocoon envelops the core of the jet, which has now a velocity around 3000 km s $^{-1}$ . The injected initial velocity was over  $10^4$  km s $^{-1}$ , meaning that the jet commonly decelerates in a rapid way after few kpc. At  $z = 22$  kpc the emission-weighted temperature reaches the maximum value of  $1.62 \times 10^7$  K (panel g), clearly indicating the effect of shock heating. Around the contact discontinuity the gas is weakly shocked, with temperatures above  $1.25 \times 10^7$  K. The average Mach number is around 1.2, a typical value found by observations (Blanton et al. 2009; Gitti et al. 2010). The arc is also visible in the SB $_X$  map (panel m), while the decrement associated with the cavity is  $\sim 35 - 40$  per cent.

Notice that the maps of this model are very similar to those of C5em4, another successful model, which has analogous bubbles production. This behaviour confirms further the strict relationship between (intermittent) Bondi and cold models, as previously noted by the compared efficiency analysis.

The last row of maps displays another snapshot, typical for intermittent (self-regulated) feedback models, like Bilem1. The big outburst and the generated bubble have been vanished, leaving the system in the aforementioned turbulent phase, in which mixing distributes the low residual heating to the central IGM. Soon after this period, the gas will cool and start the inflow. The velocity field is relatively chaotic (panel d), with maximum velocity of 640 km s $^{-1}$ , a bit lower than local speed of sound, evidently decreasing in the turbulent zones. The mixing of gas at this epoch restores the spherical symmetry of the cool core, with average temperature of  $\sim 9 \times 10^6$  K (panel h). This is underlined also by the symmetric surface brightness map (panel n) and by the substantial diffusion of Fe in the intermediate zone, 10 – 30 kpc (panel r). Note that the abundance radial profile at the very center is, however, more peaked during this quiescent cooling flow phase ( $\sim 0.8 Z_\odot$ ), compared to the AGN outburst period. Thus, our AGN models might also explain the dichotomy of cool core and non cool core groups, having the former higher central abundances (Johnson et al. 2011).

An interesting feature, captured at this stage (often present after an AGN outburst), is the sequence of very small ‘bubbles’ at  $r > 15$  kpc, with typical diameter of a few kpc. The origin of this tiny ‘bubbles’ is the fragmentation of the jet due to turbulent and chaotic motions, previously discussed. In this map they are in a very late phase, almost disappearing in the ambient medium. In this case they would be probably not detected in the X-ray (just a 10 per cent jump in surface brightness). To capture their signature, an observation should be done at an earlier evolutionary



**Figure 7.** X-ray surface brightness and emission-weighted temperature 1D cuts through  $z$  (see legend). Black thick lines correspond to the model Bilem1 (panels n and h of Fig. 6), while the others belong to model Bc5em2 (panels i and e).

moment, after a big event, when the jet is rapidly collapsing. Nevertheless, it is striking that David et al. (2009, 2010) find exactly this type of configuration in NGC 5044: few big cavities and many small ‘weather-driven’ bubbles, which appear to be radio quiet (i.e. not directly inflated by the jet).

Overall, we conclude that the AGN outflows dynamics is particularly complex, as expected from the previous study in galaxy clusters. The main stages of evolution for the best models are: (i) a gentle continuous outflow, which sustains the cooling flow for the majority of time (or always in Bc models) and which is barely observable in SB $_X$  maps; (ii) a phase of large cavity inflation, with cold rims and high density/SB $_X$  contrast (only for non-continuous models); (iii) small periods of quiescence in which the turbulence and vorticity promotes mixing and tiny weather-driven ‘bubbles’.

The presence of the above described features (big and small cavities, asymmetry of Fe abundance, low Mach shocks, etc.), is consistent with several recent X-ray observations of heated systems, and demonstrates the fundamental role of AGN driven outflows in the evolution of groups (and clusters).

## 5 DISCUSSION

In this paper we have proposed 3D numerical simulations of self-regulated AGN outflows in a galaxy group environment. We have followed the long term evolution of the interaction between two main characters: radiative cooling and feedback heating. The aim of this work is to understand the general

features of the feedback process to solve the cooling flow problem, i.e. quenching cooling rates, but, at the same time, preserving the global cool core structure.

We tested two relevant models, which we had found to be successful in galaxy clusters (Gaspari et al. 2011): cold feedback and Bondi feedback mechanisms. Galaxy groups, with masses  $\sim$  two order of magnitude less than big clusters are more fragile systems and the feedback must be consequently more delicate. In the following we discuss and summarize the main results obtained, along with merits and flaws of the models.

### 5.1 Hot continuous Bondi (Bc)

In the first set of simulations the commonly adopted Bondi prescription is applied to evaluate the accretion rate onto the black hole. Although the Bondi scenario is quite naive, it can be treated as the template model for a typical self-regulated feedback directly linked to entropy. The efficiency, as free parameter, might just incorporate the discrepancies between the ideal Bondi model and the real dynamics.

Overall, we found (similarly to clusters) that the Bondi accretion models are able to satisfy our strict requirements for a plausible evolution, with a mechanical efficiency in the range  $5 \times 10^{-2} - 10^{-1}$ . As expected, the accretion rates are always two to three orders of magnitude lower than Eddington limit. This implies that the outflow ‘touch’ is always delicate and non-explosive, with power of the order of  $10^{44}$  erg s $^{-1}$  and velocity  $10^4$  km s $^{-1}$ . These values are consistent with numerous observations of AGN outflows through absorption lines (e.g. Nesvadba et al. 2011).

In the best models cooling rates are reduced below a few or fraction of  $M_{\odot}$  yr $^{-1}$ , with a monotonic decrease in time. The density radial profiles of these models do not deviate too much from the observed ones. The same can be said of the temperature gradient, with a small overheating in the inner 4 kpc nucleus. The last feature is probably associated with the continuous nature of the feedback: the Bondi formula is in fact based on the accretion of hot gas, whose reservoir never drains.

A problem for this model may be the continuous injection of energy, which carves a tunnel in the IGM. However, as shown in Section 4, this channel is usually very narrow and almost disappears in the surface brightness image (on the contrary of events associated with big bubbles). The important result is that a feeble continuous heating could operate, without being in contradiction with observations.

The creation of cavities of tens kpc is another issue. However, we have noted that, during the increasing generation of turbulence (due to the AGN), the jet becomes gradually more disturbed: eventually it will fragment, producing a series of small buoyant bubbles. This phenomenon is certainly enhanced by a cosmological evolution through merging and other large scale motions (e.g., Morsony et al. 2010).

We have also checked that slightly different initial conditions, like an initial isothermal temperature profile and a NFW dark matter profile, do not alter the behaviour of the feedback, producing similar results.

### 5.2 Cold feedback (C)

In galaxy clusters the triggering mechanism linked to the instantaneous  $\Delta M_{\text{cold}}$  induced a very powerful outburst, often super-Eddington. In much less massive galaxy groups such a powerful feedback would easily destroy the thermal structure observed, producing negative temperature gradients up to 100 kpc. Therefore, successful models adopt efficiencies about an order of magnitude lower with respect to those used for clusters. With  $\epsilon_c$  between  $5 \times 10^{-4}$  and  $10^{-3}$  cooling rates are still well below 10 per cent of the pure CF model, but now with consistent central densities and temperatures.

The model is naturally impulsive, but this time the duty cycle is very high compared to the cluster evolution shown in G11. In fact, for the majority of time the outflow is continuous with moderate power, similar to the previous Bondi models. The AGN stays in a quiescent phase only 15-20 per cent of the time, after which it will ignite with outbursts up to  $10^{45}$  erg s $^{-1}$ . These powerful jets are essential for creating big bubbles of 10-20 kpc diameter.

One of such event has been analysed in Section 4 (Fig. 6). The bubble does not show high temperature within (e.g.  $10^8$  K or more), like in clusters (G11): it is very underdense with respect to the ambient medium, with a relatively large contrast in the SB $_X$  map ( $> 50\%$ ). It is striking that the metal abundance is often highly asymmetric, enhanced along the outflow direction. All the previous features are commonly present in deep X-ray observations (McNamara & Nulsen 2007; Baldi et al. 2009; Gastaldello et al. 2009; Kirkpatrick et al. 2009, 2011; Rasmussen & Ponman 2009; David et al. 2009, 2010).

Overall, it is surprising that, in galaxy groups, models with cold feedback resemble, most of the time, simulations with Bondi accretion, with the merit of adding important features like X-ray cavities and ripples at larger radii (essentially weak shocks with Mach around 1.1 – 1.3). This fact clearly indicates the necessary properties of the feedback process, if outflows are the main mechanism: very frequent or almost continuous and gentle.

### 5.3 Bondi with cold timing (Bi)

Simulations using the third class of models, Bi, have been carried out to test the combined effect of Bondi accretion and cold triggering mode, in order to avoid Bondi continuous injection (intrinsic in the ideal case). In some preliminary tests (here not shown), we found that a simple superposition of the two feedback schemes leads to unacceptable models, because the outcome is just a more powerful jet, which carves a larger and deeper continuous channel.

Therefore, we tried another way to combine both methods. Keeping Bondi accretion prototype (entropy-regulated) for the value of power, we assumed that when the gas begins to cool at the center (i.e. the inflow initiates), the feedback is activated. This will prevent too peaked instantaneous outflow powers and, at the same time, the AGN activity acquires a sort of duty cycle.

The results are very encouraging. The required Bondi efficiency for best models stays again in the range  $5 \times 10^{-2} - 10^{-1}$ . Assuming  $\epsilon_B < 10^{-2}$ , the evolution manifests the typical flaws of a pure CF run. On the contrary, if  $\epsilon_B > 10^{-1}$  the feedback becomes very explosive and easily ‘burns’ the cool

core. The best Bi models show instead radial profiles with gradients not far detached from the initial observed state, along with very low cooling rates (usually one or less solar masses per year).

The look of the Bi simulations has been analysed, in-depth, in Section 4. The general features are almost identical to the previous discussed models. Extensive periods of a continuous Bondi-like injection ( $\dot{P}_j \sim 10^{44}$  erg s $^{-1}$ ,  $v_j \sim 10^4$  km s $^{-1}$ ) produce a narrow heating channel, alternated with dormant AGN phases ( $\sim 15\%$ ). As in the cold feedback computations, the short inactivity promotes the subsequent generation of outbursts with greater power (3-4 times more than the continuous phase), producing important observed features, such as tens of kpc cavities and oscillations in the flow quantities.

It is relevant to note that, as in previous good cold models, only a fraction of the injected mechanical energy is used to inflate cavities (usually under 50 per cent<sup>9</sup>). One of the main results, also pointed out in G11 for clusters, is that the success of a feedback crucially depends on how the energy is transferred to the surrounding medium, not only on the total amount of available energy. Furthermore, the heated flow has a very complex dynamics, with numerous facets. After the mechanical energy is injected in the system, a part of energy inflates the bubble, but the rest generates the cocoon and weak shocks. When the jet is more continuous, the moderate energy released at intermediate radii induces a turbulence growing in time. These chaotic motions permits a more efficient circulation of the hot gas, promoting the deposition of energy through mixing at the base of the jet, where the cooling tends to dominate. Furthermore, while the system becomes more turbulent, the feeble jet can be fragmented and can cyclically produce tiny ‘bubbles’, few kpc in size (albeit very faint in the SB<sub>X</sub> map). Their buoyant motion may promote additional mixing and heating, helping the global feedback process. Quite simple feedback models still generate an amazing variety of heating processes.

As a concluding remark for these models, the efficiency comparison underlines again the strict relationship with the cold best models, exactly around  $\epsilon_c \sim 5 \times 10^{-4} - 10^{-3}$ . We can therefore affirm that the feedback in galaxy groups, able to quench cooling flow but at the same time preserve the cool core structure, is globally only of one type: moderate, gentle, often continuous and turbulent, with very short periods of inactivity and following outbursts.

#### 5.4 Rejected models

It is also interesting to highlight the main features of unsuccessful models, in order to understand why some kinds of feedback do not work.

First of all, while a small part of the total energy injected could be in thermal form, above a threshold fraction of  $\approx 50\%$  the center of the group becomes too hot with respect to the observations (see also Brighenti & Mathews 2002, 2003). Injection of a modest amount of thermal energy

can have the beneficial effect of disrupting the otherwise ordered structure of the outflows (Section 3.5). This model intermittently eliminates the long tunnel, usually not observed in real systems. Moreover, the deposition of heat in the nucleus helps preventing the formation of a cold torus. Injection of thermal energy can be justified assuming that shocks heat the hot IGM in the very central region.

Another rejected model considers the active outflowing mass directly linked to the real accreted mass onto BH (In-Out feedback, Section 3.6). The main problem here is that, even with very low  $f_{in}$  (e.g.  $f_{out} > 0.9$ ), the jet velocity often exceeds  $10^5$  km s $^{-1}$ . This unappealing result can in principle be fixed adding a mass loading factor ( $\eta f_{out}$ ; see also Cattaneo & Teyssier 2007; Ostriker et al. 2010). However, this assumption will mimic entrainment, just as our standard outflow generation method described in Section 2.2. It is not surprising therefore that we recover acceptable results, similar to those described in Sections 5.1.

Intermittent models (Section 3.4), with fixed jet power, are only partially acceptable, as was also found for galaxy clusters (G11). The most successful run has relatively weak outflows ( $\dot{P}_{jet} \sim 10^{-4} \dot{P}_{Edd}$ , activated every 10 Myr, with a duration of 5 Myr each (model Int510m). We have also tested jets with Eddington power ( $\sim 10^{47}$  erg s $^{-1}$ ). As expected they will destroy the cool core generating systems very different from the real ones.

Probably the major flaw of the intermittent models is their artificial nature. Cooling rates can be suppressed, compared to a pure CF model, but the temperature profiles oscillate strongly in the center. This further supports the common notion that heating *must* be self-regulated.

Finally, we have briefly investigated the effect of jet precession (not shown). Important parameters like inclination angles and revolution time of the jets are currently poorly known. Nevertheless, we found that the behaviour of cold gas at the base of the outflow, i.e. the formation of a small cold torus, is not greatly different from non-precessing models. In fact, the heating channel will be again generated after the first episodes, getting a tilted orientation in respect to a normal  $z$ -axis cylindrical simulation.

#### 5.5 Comparison with galaxy clusters

As expected, our simulations show that AGN heating has a deeper impact in galaxy groups than in clusters, because the same mechanical power per particle has a greater effect for a lighter, less bounded systems.

As we have seen in the previous Sections, a jet with Eddington power can easily erase the entire thermodynamic structure of the cool core. The same applies for all the self-regulated simulations with very high efficiencies ( $> 5 \times 10^{-3}$  for cold models;  $> 10^{-1}$  for Bondi). In G11 we showed that consistent cold models commonly produced super-Eddington outbursts ( $> 10^{47}$  erg s $^{-1}$ ), with a very low frequency ( $\sim 10$  per cent). Despite the huge power injected, the shock-heating phase could not destroy the observed density and temperature gradients, and the cluster quickly restored the usual cool core. The only marked consequences were more ripples at larger radii and cavities, which in the early phase presented high internal energy and shocked rims.

On the contrary, galaxy groups, with much less binding energy (per particle), can not recover from the same strong

<sup>9</sup> E.g., the inflation energy of the bubble in Fig. 6, panel b, is  $4PV \sim 4(2 \times 10^{-11} \text{ erg cm}^{-3})(1.1 \times 10^{68} \text{ cm}^3) \approx 9 \times 10^{57} \text{ erg}$ , while injected mechanical energy is  $2.45 \times 10^{58} \text{ erg}$ . Thus, inflation energy is just 37% of the total injected energy in that single event.

impulsive feedback. In order to prevent such ‘heating catastrophe’, cold feedback models in galaxy groups require an efficiency at least 5 – 10 times lower. The outcome is striking, because the evolution resembles that of Bondi models, with low power jets ( $10^{44} - 10^{45} \text{ erg s}^{-1}$ ) activated in a quasi-continuous gentle way. These outbursts occurring after short quiescence periods (tens Myr) generate  $\sim 10$  kpc cavities surrounded by relatively cold rims in the region close to the center of the group, similar to some observations (e.g., Gastaldello et al. 2009). Unlike in galaxy clusters, cavities in groups present the usual low density contrast, with temperatures similar to the surrounding medium.

The best models assuming continuous Bondi accretion, on the other hand, are equivalent in both clusters and groups (except for the efficiency, lower in groups). Accretion rates always follow a sub-Eddington regime. The moderate outflows carve a narrow tunnel in the intergalactic medium; we showed, in this paper, that it is very faint in the SB<sub>X</sub> map and thus hard to resolve. The absence of inflated bubbles is still a riddle of this type of feedback. Notice that in galaxy clusters the low-power outflows ( $\epsilon_B = 0.1$ ) had more difficulty in halting the massive cooling flow (tens  $M_\odot \text{ yr}^{-1}$ ), showing more peaked density profiles. Therefore, in clusters, cold accretion was slightly favoured as an acceptable model.

Another common feature in both clusters and groups is the asymmetrical distribution of metals (mostly iron) produced by the SNIa in the central galaxy. They tend to accumulate along the jet axis, in qualitative agreement with recent observations (see Sec. 4).

In all the consistent group models the sub-Eddington outflow powers imply that the total injected energy (a few  $10^{61}$  erg for the full-space system) is always an order below the total ‘available’ BH energy. In fact, during the simulated evolution, the black hole mass increases at most 10 per cent in Bondi models. In the cold feedback model the lower efficiencies imply a much higher  $\Delta M_{\text{BH}}$ , similarly to galaxy clusters. As noted in G11, however, the real efficiency (still unknown) could just be higher, with a lower mass actually falling onto the BH.

Our simple approximation of the real sub-pc accretion does not allow to answer why the efficiency in groups should be a factor 5-10 smaller than in clusters, aside the observational requirement. It would be interesting to investigate this topic with a dedicated analysis.

## 6 CONCLUSIONS

Here we summarize the main conclusions of our study.

i) Feedback triggered by both Bondi accretion and cold mode accretion (or a combination) lead to successful self-regulated models. These schemes are able to quench cooling flow for many Gyr, preserving the observed thermal structure of relaxed groups. The required mechanical efficiencies for cold accretion models are in the range  $5 \times 10^{-4} - 10^{-3}$ , while  $5 \times 10^{-2} - 10^{-1}$  for the Bondi scenario.

ii) In the galaxy group, the two main feedback schemes generate similar flows. The global evolution is dominated by almost continuous outflows, with sub-Eddington power ( $10^{44} - 10^{45} \text{ erg s}^{-1}$ ) and velocities around  $10^4 \text{ km s}^{-1}$ . These values are consistent with those based on observa-

tions of AGN outflows (Crenshaw et al. 2003; Morganti et al. 2005, 2007; Nesvadba et al. 2008, 2011).

iii) The main feature of the continuous phase is a narrow tunnel (large a few kpc, up to 30 kpc long), which is almost undetectable in the SB<sub>X</sub> map. The tunnel is periodically fragmented by the increasing AGN-driven turbulence, especially when the BH is in a phase of low accretion. The products are tiny, kpc-size buoyant bubbles, which help the mixing of the IGM. These faint features are very difficult to detect, but seen in a few systems, most notably NGC 5044 (Buote et al. 2003; David et al. 2009, 2010).

iv) Cold and hybrid accretion models show short quiescent periods (summing to a  $\sim 15\%$  of the evolutionary time). Each quiescent period is followed by a relatively strong outburst, with power about an order of magnitude larger than the typical value during the continuous phase. The consequence is the creation of relatively large cavities (10 – 20 kpc), with high density contrast, in approximate pressure equilibrium with the ambient. The emission-weighted temperature in the cavity region, however, is not far above those of the surrounding medium. Feeble rims, relatively cold in the region near the center and slightly hotter in the more distant part, with somewhat higher iron abundance, are also present. These features are again reminiscent of real systems (McNamara & Nulsen 2007 for a review, Gastaldello et al. 2009; David et al. 2009).

v) The asymmetrical transport of metals, along jet-axis, up to 40 kpc, is clearly visible during the active phases. In quiescent periods, the moderate turbulence promotes metal diffusion. Recent observational data confirms this behaviour (Kirkpatrick et al. 2009, 2011; David et al. 2010).

vi) Finally, the global point of all our computations: the only possible way to heat a galaxy group, in order to suppress the grip of the cooling flow, appears to be through a quasi-continuous ‘delicate touch’, while in massive clusters rare and explosive strokes are mildly favoured over the weaker Bondi regulation. This quite different feedback evolution might explain the common observed discrepancies between the two cosmological actors. Galaxy groups are indeed not purely scaled-down versions of galaxy clusters.

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